Service Design for Heavy Demand Corridors: Limited-Stop Bus Service

By

Stacey Schwarcz

B.A., Mathematics
Brooklyn College, City University of New York, 1998

Submitted to the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirement for the Degree of

MASTER OF SCIENCE IN TRANSPORTATION

at the

Massachusetts Institute of Technology

September 2004

Signature of Author ______________________________
Department of Civil and Environmental Engineering
August 13, 2004

Certified by ______________________________
Nigel H.M. Wilson
Professor of Civil and Environmental Engineering
Thesis Supervisor

Certified by ______________________________
John Attanucci
Thesis Supervisor

Accepted by ______________________________
Heidi Nepf
Chairman, Committee for Graduate Studies

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Abstract

Many transit agencies run both limited-stop and local service along some of their heavy ridership corridors. The primary benefit of limited-stop bus service is higher speed which results in reduced running time and thus reduced travel time for passengers. This reduced travel time can improve the service quality for existing passengers and can increase ridership on the route and thus both passengers and the agency can benefit from limited-stop service. However, this strategy also results in increased access time, and in increased wait time for some passengers. This thesis develops a model to evaluate limited stop bus service and then applies the model to develop general design guidelines for limited-stop service.

The model created evaluates a specific service configuration including both the local and limited-stop headways and stops. The model calculates travel times, and assigns existing demand to limited and local stops and to limited and local routes, based on minimum passenger (weighted) travel time. This assignment is applied at the origin-destination pair level. The model then calculates several measures of effectiveness, which are used to compare different configurations, including market share (local preferred, limited preferred, and choice passengers), stop and route assignment (number of passengers selecting the limited service stops and limited-stop service), net change in passenger travel time (weighted and un-weighted), and finally productivity (passengers per trip and per vehicle hour for the local and limited-stop service).

The model was used to analyze two CTA cases: Western Avenue local Route 49 and limited-stop Route X49, and the Madison Avenue Route 20. The analysis of Western Avenue and Madison Avenue involved testing alternative frequency configurations; alternate stop spacing configurations were analyzed only for Madison Avenue. The specific findings on these routes show that the existing stop spacing on Route X49 is effective, but to improve the overall effectiveness of the route the limited-stop frequency share should be increased to at least 60% of all service on the corridor. Limited-stop service on Madison Avenue was found not to be effective under any configuration due to short trip lengths and evenly distributed demand along the route.

The results of the analysis were used to develop two sets of guidelines: corridor (or route) potential for limited stop service and limited-stop service design. The corridor potential guidelines suggest that high concentrations of origins and destinations and long passenger trips are both critical to the effectiveness of limited-stop service. Additional factors that

affect the corridor potential for limited-stop service are the existing headway and ridership and the potential for route level running time savings.

Limited-stop service design guidelines were developed for setting stop spacing and frequency share. The stop spacing on the limited-stop service should be decided by placing stops at the highest demand points and at all transfer points, and is guided by the distribution of origins and destinations, with the goal of attaining a wide enough stop spacing to achieve significant route level travel time savings. One of the major findings of this thesis is that limited-stop service is generally most effective at greater than 50% frequency share.

Thesis Supervisor: Nigel H.M. Wilson
Title: Professor of Civil and Environment Engineering
Thesis Supervisor: John Attanucci
Title: Research Affiliate, Civil and Environmental Engineering

Acknowledgements

I am extremely grateful to all of the people who gave me guidance, encouragement, inspiration, and friendship during my two years at MIT.

I am especially grateful for the guidance of my thesis advisors Nigel Wilson and John Attanucci. Nigel, thank you for all of the time that you put in to my work, for pushing me to do my best, and for teaching me to think critically. John, thank you for your time and for showing me how to take a step back from my work and see the big picture.

I thank the Transportation faculty and staff at MIT and Northeastern University. Special thanks to Mikel Murga, Fred Salvucci, Peter Furth, and Ginny Siggia.

I am also grateful for the advice and help of my classmate Jeff Busby, my unofficial advisor. Thank you for always being generous with your time and for your encouragement.

I thank CTA for all of their support with this research.

I thank the MBTA for all of their support with this research and for hosting me in the planning department last summer.

I am grateful to my family and friends for all of their support. Special thanks to my parents Michael and Jo Ellen, and to my sisters Chaya and Rivka for your love and support throughout these two years. Special thanks to my friends Aviva Presser, Aurore Zyto, Esther Friedman, and Rachel Miller who have probably heard more about limited-stop bus service than they ever wanted to know.

Finally, thanks to all of my friends and classmates at MIT who contributed to this thesis and helped to make my time at MIT memorable. Special thanks to Isaac Moses, Bassel Younan, Anjali Mahendra, Julie Kirschbaum, Damian Raspall, Zabe Bent, and Miguel Molina.

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1 INTRODUCTION

This thesis will focus on the evaluation and design of limited-stop bus service. Bus routes in the United States tend to have closely spaced stops, sometimes with as many as 12 stops per mile (Furth and Rahbee, 2000), which results in slower travel speeds and thus longer passenger travel times. Due to the political ramifications of increasing stop spacing which often stem from accessibility concerns for people with disabilities or other mobility issues, it is often difficult to increase stop spacing on a route. This is a primary reason that agencies have turned to limited-stop bus service.

Limited-stop bus service generally operates on the same street as local service, but with fewer stops. This strategy allows the agency to effectively increase stop spacing and thus increase travel speed while still maintaining closer stop spacing on the local service. It is an attempt to ensure accessibility for those who cannot, or do not want to, walk an additional distance, while reducing travel times for other passengers. However, even for the greater portion of passengers who will walk an additional distance there is still a trade-off between reduced travel time and increased wait time as well as walk time, and it is thus possible to make passengers worse off overall by instituting limited-stop service. Therefore, creating an effective limited-stop bus service requires careful planning.

Limited-stop bus service has been implemented by several transit agencies, including the Chicago Transit Authority (CTA), New York City Transit (NYCT), the Los Angeles County Metropolitan Transportation Authority (MTA), and the Massachusetts Bay Transportation Authority (MBTA). Some of these agencies have conducted market research on limited-stop bus service (Silverman, 2003, CTA Market Research, 2000 and 2003) have experimented with various configurations of limited-stop and local service (MTA, 2003), or have some guidelines pertaining to limited-stop service based on the past experience of the agency (Silverman, 2003, MTA, 2003). However, there are still many questions left unanswered. These questions include how to evaluate a route where the addition of limited-stop bus service is being considered; how to determine stop spacing on the limited-stop bus route; how to determine the mix of limited-stop versus local service, and what combination of factors are likely to result in successful limited-stop service (Silverman, 2003).

These questions will be addressed in this thesis primarily through the development and the application of a model which estimates travel time savings and other measures of effectiveness in order to compare various configurations of limited-stop service. This method allows for a detailed analysis of the effects of changing the limited-stop service configuration which takes into consideration changes in wait time, access time, and in-vehicle time. It allows for a careful analysis of where there are passenger travel time reductions and increases in order to determine what type of configuration will prove most effective. A primary goal of this thesis is to establish guidelines based on this analysis for the addition of limited-stop service and the evaluation and reconfiguration of existing service.

1.1 Motivation

Many transit agencies run both limited-stop and local service along some of their heavy ridership corridors. The primary benefit of limited-stop bus service is faster speed which results in reduced running time and thus reduced travel time for passengers as well as greater productivity for the agency. This reduced travel time increases the level of service for existing passengers and can increase ridership on the route: the NYCT has found that passengers perceive limited-stop bus service as saving twice the time that they actually save (Silverman, 2003) and the CTA has found that limited-stop service has increased ridership by 3 to 4% on the routes where it has been added (CTA Market Research, 2000 and 2003). The limited-stop bus service strategy therefore has the potential to benefit both the agency and the passengers. However, this strategy also results in increased walk access time, and in increased wait time for some passengers, especially when the strategy is considered in the context of a fixed operating cost or resource neutral strategy, which means that no additional resources are added and the creation of the limited-stop bus service requires splitting the existing local resources between the limited-stop service and the local service. These tradeoffs need to be carefully analyzed before limited-stop bus service is implemented (or modified) on a corridor. The findings of this thesis will be valuable to operators in general, but specific CTA routes will be used as case studies.

CTA currently runs 5 limited-stop bus routes and additional limited-stop services are being considered. The first CTA limited-stop bus route created was the X49 operating along Western Avenue in a north/south direction about 2 miles west of the downtown area. The X49 service began operating at the end of 1998 and was created by adding resources to the route. Since the introduction of the X49, four additional limited-stop bus routes have been created: the X3, X4, X55, and X80. Despite several years of experience with limited-stop bus service, there is still uncertainty about the best way to evaluate a new or existing limited stop bus service and how to configure limited-stop service (CTA Market Research, 2000).

Currently at CTA, the creation of new limited-stop bus service must be resource neutral or very close to resource neutral. This is a phenomenon that is now common to many transit agencies due to financial constraints. NYCT policy is to create resource neutral limited-stop bus service and likewise the MBTA in Boston will only consider new limited-stop bus service in a resource neutral context. The addition of limited-stop bus service constrained to be resource neutral, or requiring only slight resource increases, is more risky than creating limited-stop bus service by adding resources because a poorly designed resource neutral limited-stop service can result in a decrease in overall service quality as measured by net travel time changes for passengers. In light of this, there is a pressing need for clear guidelines for evaluating potential limited-stop bus service routes and for reconfiguring existing service. Thus, one of the primary goals of this thesis is to provide analytically based guidelines to transit agencies in order to assist in decisions concerning limited-stop bus service.

1.2 Objectives

There are three primary objectives of this thesis. The first is to create a model that can be used to analyze limited-stop bus service. The second is to apply the model to CTA case studies. The third is to develop guidelines that transit agencies can use for the evaluation and design of both new and existing limited-stop bus service.

1.3 Methodology and Approach

This thesis will consider previous research conducted by transit agencies and academic sources and then conduct further research in order to establish guidelines that can be used by a transit agency to select potential limited-stop bus routes and to configure limited-stop bus service.

To accomplish the objectives of this thesis, the following steps are necessary:

1. Review of relevant prior research and limited-stop bus routes in other cities
2. Develop a limited-stop model
3. Application of the model to CTA case studies
4. Develop guidelines for the addition and design of limited-stop bus service

The goal of the first step is to build a foundation of knowledge from academia and from the practical experience of transit agencies. This includes a literature review and summaries of the experiences of those transit agencies that operate limited-stop bus service. The references for this information are from several sources. These include formal journals, websites, reports produced by the transit agencies, and interviews with the transit agencies. The reason for this first step is to evaluate current research on limited-stop service and to determine which areas lack information or require further research and to critically assess commonly held views on limited-stop bus service, specifically in the following areas:

- Stop Spacing on the limited-stop service
- Limited-Stop Frequency Share

As an example, some transit agencies believe that a 50% frequency share is the best way to configure limited-stop service; however, this concept has not been analytically or experimentally tested since these agencies have not attempted to operate service at any other frequency share (Silverman, 2003; Silverman, Gawkowski, et al., 2003). This idea and others like it will be challenged in this thesis.

The goal of the second step is to create the model that will be used to analyze limited-stop service. The model created for this research is designed to evaluate a specific service configuration: meaning that the local and limited-stop headways and stops are specified. The model estimates travel times, and assigns existing demand to limited and local stops and to limited and local routes, based on expected minimum passenger travel time. This assignment is done at the origin to destination level. The model then calculates several measures of effectiveness which are used to evaluate the service configuration. These measures of effectiveness will be discussed in detail in Chapter 2. The model requires as inputs information about the route structure, running times, and demand which in general can be obtained either from manual observations and passenger counts or from automated passenger counting and vehicle location data as in the case of the CTA routes.

The model is based on the following two key assumptions: demand is fixed and vehicle capacity is not binding. The fixed demand assumption means that it is only the assignment of demand that varies with the service configuration. It is recognized that increased demand resulting from reduced travel time and overall increase in the level of service may well result; however, this is not considered explicitly in the model. The assumption is that the configuration which produces the best level of service for existing passengers will also be most likely to induce new ridership.

The assumption that the vehicle capacity is non-binding implies that all passengers can board the first bus to arrive. If this assumption is violated then this would affect the passenger waiting times calculated in the model. To account for this problem, one of the measures of effectiveness that will be considered is productivity, measured as average passengers per trip; if this measure shows passenger loads at, or above, the capacity, then this would indicate a problem with the configuration.

The third step is to apply the model to the case studies. The model is used to evaluate a specific configuration so that the positive, negative, and total effects of changing the configuration of limited-stop service can be analyzed. The model will be applied to the case studies to evaluate several stop spacing and frequency configurations and to perform additional sensitivity analysis, including changes in the demand pattern on the route, and in the travel time weights that are used in the model to represent passenger travel time perceptions of access time, wait time, and in-vehicle time.

The sensitivity analysis is necessary to set up relationships between various limited-stop route characteristics that will form the basis for the guidelines which are developed as part of the step four. These relationships include the following:

- Effect of passenger perceptions on the assignment process (passenger perceptions are reflected through the use of travel time component weights)
- Effect of the frequency share on the effectiveness of the route
- Interaction between passenger trip lengths and travel time savings
- Effect of the origin and destination (O-D) demand concentration on the effectiveness of the route

The guidelines will address the interactions between these factors, and will allow a transit agency to evaluate new or existing limited-stop bus service based on potential travel time savings, available resources, passenger trip lengths, and the O-D concentration on the route. The following components are the key components of limited-stop bus service which will be addressed directly by the guidelines:

- Stop reduction and spacing
- Running time savings
- Frequency split
- Resources: Existing and Added
- Passenger trip length
- O-D concentration
- Passenger Travel Time Perceptions

Stop Reduction: this is the defining characteristic of limited-stop bus service. Current practice at the CTA, the NYCT, and the MTA is to set average stop spacing at between 0.3 and 1 mile; with wider stop spacing in less dense areas and closer stop spacing in denser areas such as the downtown area.

Running Time Savings: running time savings significantly impact the success of limited-stop bus service. For standard limited-stop bus service the amount of running time saved depends on the number of stops and the nature of the traffic on the street. In practice, running time savings at the CTA range from 15 to 23%, which is comparable to the experience at the NYCT and the MTA.

Frequency Share: the frequency share refers to the percentage of total service on the route that is limited-stop service. In practice this is often set at 50% (Silverman, 2003), but at MTA it is sometimes increased to greater than 50% on Metro Rapid routes due to the high demand for Metro Rapid service (Chapman, 2004).

Existing and Added Resources: The resources, meaning the number of buses, available for both the local and limited-stop service will be a contributing factor to the success of the route. Limited-stop bus service can be created by adding all new resources for the limited-stop service or at the other extreme as a resource neutral change or with some mix of existing and new resources. In practice most agencies including the CTA and the NYCT currently only consider resource neutral limited-stop service. In fact nearly all limited-stop routes that the NYCT has created have been resource neutral changes (Silverman, Gawkowski, et al., 2003).

Passenger Trip Length: Net time savings potential is greater for longer trips, defined as trips greater than two miles, since the in-vehicle time savings are more likely to be significant enough to counteract the increased access time. The higher the percentage of trips greater than two miles then the greater the effectiveness of limited-stop bus service. Currently no guidelines exist at the NYCT, the CTA, or the MTA concerning passenger trip length and limited-stop service.

O-D Concentration: Limited-stop service will be more effective on corridors where demand is highly concentrated at origins and destinations, since this will maximize the number of passengers at or near limited service stops and thus maximize the number of potential limited-stop service riders. High O-D concentration also means that there are fewer high demand stops and thus more stops can be eliminated resulting in higher travel time savings which will result in more effective service.

Passenger Travel Time Perceptions: Studies such as the Chicago Area Transportation Study (CATS) have shown that passengers perceive wait time, walk access time, and in-vehicle time differently. In general both wait time and access time are seen as more onerous than in-vehicle time and access time is seen as more onerous than wait time. Passenger travel time perceptions will affect whether passengers walk further and how far they are willing to walk to get to a limited stop if the passenger trip does not begin and/or end at a limited stop. This will affect the viability of limited-stop service under a particular configuration.

1.4 Thesis Organization

The remainder of this thesis is divided into four chapters. Chapter 2 contains the background information on limited-stop bus service, a literature review, measures for evaluating limited-stop service, and procedures and experiences with limited stop service in other cities. Chapter 3 contains the model specification and approach. Chapter 4 contains the validation of the model and the application of the model to CTA case studies. Chapter 5 contains the guidelines. Chapter 6 summarizes this work, provides recommendations to CTA, and provides suggestions for future research on this topic.

2 LIMITED-STOP SERVICE

This chapter will provide a more detailed description of limited-stop bus service and a review of the prior research conducted on this topic or related topics. The evaluation measures which are critical to the analysis of limited-stop bus service and to the later development of the guidelines will also be explained in this chapter.

2.1 What is Limited-Stop Service?

There are a number of strategies for dealing with high volume or heavy demand bus service corridors. A heavy demand corridor will be defined here as one which can support a headway of ten minutes or less during the peak period. These strategies include zonal express service, short turning, restricted zonal service, and limited-stop service. These strategies will each be described briefly later in this chapter as part of the literature review; however, this work will focus exclusively on limited-stop bus service. More specifically, this thesis will focus on corridors with both limited-stop and local service.

Limited-stop service is a variation on local service with more widely spaced stops. Local stop spacing generally ranges from fewer than 4 stops per mile to more than 12 stops per mile (Furth and Rahbee, 2000). Limited-stop spacing is generally between one-third of a mile and one mile, or 1 to 3 stops per mile. This reduced stop spacing allows for reduced overall travel time and running time compared with the local service. This primary benefit of limited-stop service can result in benefits to both the passengers and the agency.

The move toward wider stop-spacing and limited-stop service can also be a first step toward BRT (Bus Rapid Transit) which includes dedicated lanes and/or signal priority. Limited-stop service has also been shown to help retain ridership. In fact, New York City Transit market research has shown that people respond very well to it, usually out of proportion to the quantifiable benefits of reduced travel time (Silverman, 2003).

However, there are also some negative associated with limited-stop service including increased access time for some limited-stop passengers and "choice" riders and increased wait time for "local preferred" riders. Choice riders are passengers who will walk further to (or from) stops with limited-stop service so that they have the option of taking the limited-stop service. Local preferred passengers are riders who choose not to walk, or cannot walk, to (or from) a further limited stop and thus take only the local bus. Increased wait time is a more significant issue when the limited-stop service is created in a resource neutral situation, so that prior local resources are now split between the limited-stop and the local service, significantly reducing frequency at local-only stops. This research will primarily consider the addition of limited-stop services in the resource neutral situation so this issue will be analyzed and addressed.

Some of the issues surrounding limited-stop service include stop spacing, frequency on the local and limited-stop, span of service, marketing, and scheduling. This research will focus only on stop spacing and frequency; however, these other issues are also important and will be addressed later in this chapter as part of the review of experiences in other cities including New York and Los Angeles.

2.2 Literature Review

The previous academic research on limited-stop service is sparse, and it appears that overall there is minimal general information in the area. Some of the information available is not exclusive to limited-stop service but rather discusses limited-stop service as part of a broader review of service design strategies. Of the general information that exists, the most extensive information is from the practical perspective of transit agencies and is based largely on experience. The literature review that follows includes reports on general service design strategies, specific limited-stop resources and sources on stop-spacing, frequency and other issues of relevance. This review will be organized into the following three categories:

1. Service Design Strategies for Heavy Demand Corridors
2. Limited-Stop Service
3. Modeling Limited-Stop Service

2.2.1 Service Design Strategies for Heavy Demand Corridors

Limited-stop service is one of several possible service strategies which can be used on heavy demand corridors. Furth and Day (1985) provide an overview of these various design strategies which include zonal express service, short-turning, restricted zonal service, semi-restricted zonal service, and limited-stop service. Furth, Day, and Attanucci (1984) provide a more in-depth analysis of the alternate design strategies. The goal of these studies is to define operating strategies that make it possible to serve existing ridership on moderate to high demand radial corridors at lower cost and/or with better service quality.

Zonal express service is a strategy where service is split into several zones and each bus serves all local stops within its service zone, and then operates express to or from the central business district. The primary advantage is a significant reduction in in-vehicle travel time. The disadvantage is increased wait time since headways are higher within any zone. The operator achieves lower cost through this strategy due to the reduced running time and hence higher productivity.

Short-turning is a strategy that involves two (or more) service patterns along the same street. One pattern operates on the full route and the other "short-turns" at one (or both) end(s) of the route. This strategy is used when there is low demand at the outer end(s) of a heavy demand corridor. The advantage of this strategy is reduced operating cost due to reduced running times on short-turned trips; this is an advantage to the agency but there could be benefits for passengers traveling within the common section if the agency maintains the same level of resources since the frequency would increase. However, there is a disadvantage in the form of wait time increases for passengers whose trips are beyond the common section.

Restricted zonal service is similar to zonal express service in that service is split into several zones and all local stops are made within its service zone. However, it differs from zonal express service in that the bus operates along the local route and thus can stop at any stop outside its service zone, but only to allow passengers to alight on inbound trips and board on outbound trips. The advantage of this strategy is reduced travel time due to skipped stops and thus lower operator cost. The disadvantage is increased wait time since headways are higher in any zone.

Semi-restricted zonal service is similar to restricted zonal service except that if an inbound bus stops outside its service zone to allow a passenger to alight then it will also allow waiting passengers to board at that stop. However, this does not work in the outbound direction, since passengers cannot count on a bus stopping outside the designated zone. Thus the strategy can only be used in the inbound direction and is in general very confusing for passengers. This strategy can reduce running time and so reduce the operator cost.

Limited-Stop Zonal Service is the final strategy discussed. Limited-stop zonal service as described is a strategy in which the bus stops at all local stops in its service zone, but full service stops outside the zone are spaced between 0.5 miles and 1 mile apart. A parallel local route runs along the same street and makes all local stops. The strategy creates a "choice" market, where some passengers can take either the limited-stop or the local. The advantage of this strategy is reduced travel time. Disadvantages include increased access time for some passengers and increased wait time for passengers who take only the local service. This strategy is generally cost neutral rather than cost reducing and is used to increase the efficiency of service on a route by decreasing overall travel times.

2.2.2 Limited-Stop Service

The following sources deal exclusively with limited-stop service.

Sholler (2003) provides background information and sets up a qualitative framework for analyzing limited-stop service. Headway, span of service, stop spacing, route length, and reliability are cited as service design issues. Travel behavior, travel attitudes and preferences, and socio-economic characteristics are noted as market characteristics that should be part of the evaluation of limited-stop and express service. An evaluation matrix is presented which includes these service design issues and market characteristics. Policy and operational requirements are presented at the end of the work which include data collection, policy and operating goals, and monitoring issues.

Ercolano (1984) studies peak period limited-stop service at New York City Transit as an intermediate service between local and regional express service. One primary focus of this paper is on the use of limited-stop service to reduce the number of peak period vehicles needed by reducing running time and thus annual operating and capital costs. The paper also considers how the increase in operating speeds that results from limited-stop service can help retain current ridership and possibly generate new ridership. There is a distinction made between "limited-stop service" and "modified limited service". Limited-stop service as defined in this paper is a route that makes limited-stops in several portions of the route and then makes local stops in other portions so that it is not a fully limited-stop service. Modified limited-stop service as defined in this context is what is generally thought of when referring to limited-stop service, where limited-stops are made on most (or all) of the route.

Data was used from 15 Manhattan bus routes. Relationships between travel time and route distances were established using linear regression. The results are presented for local, limited-stop, and modified limited-stop. The conclusion of this analysis is that "after a steady rise in travel time savings a point of diminishing returns may be reached for route lengths longer than 9 miles; however, actual time savings are greatest for the longest routes" (pp. 25-26).

Economic analysis and comparison was done for the routes studied. This analysis included estimating total capital and operating cost, the relative share of total cost that these represent, and the degree of savings possible from limited-stop and modified limited-stop operations. A detailed analysis was conducted of the various cost components. The conclusions reached were that the capital cost savings resulting from reduction in peak vehicles needed would account for the greatest proportion of cost savings obtainable from limited stop scheduling. "Decreases in fleet size ranged from 2 to 11 buses per route depending on stop service [sic], route length, and headways" (pp. 26).

A small percentage of trips were surveyed to analyze passenger preference and the use profiles show that there is similar ridership attraction for local and limited buses. No definitive statements could be made due to the small sample size; however, it appears from the load profiles that limited service was being used to a significant degree on the routes surveyed. A survey of ridership preferences was conducted at high volume locations for three limited routes. The results showed that 50-60% of peak riders preferred the limited when available, which is also supported by boarding counts. In addition about 12% of those responding walked beyond their nearest bus stop. Observations made concerning simultaneous arrivals of local and limited buses found that between 42% and 74% of total boardings were made on limited buses. Modified limited service was not surveyed, but based on previous research the assumption is made that there would be even higher levels of passenger use for this type of service than for the limited-stop service.

The paper's recommendations include:

- User travel time reductions of more than 5 minutes per trip are generally necessary for time savings to be perceived by riders or significant enough to justify limited service in terms of operating cost reductions.

- Studying the potential use of peak-period limited service by analyzing origin-destination by route and route segment

- The number of buses assigned as limiteds can be approximated by the percentage of longer distance trips expected per selected route

2.2.3 Modeling Limited-Stop Service

This third category reviews research that was helpful in designing the limited-stop model developed in this thesis. It includes work on origin-destination (O-D) matrix estimation, passenger waiting time, stop spacing, and limited-stop service attributes as they relate to BRT.

Origin-Destination Matrix Estimation

An Origin-Destination (O-D) matrix is used in the limited-stop model developed in this research. There are several ways to estimate an O-D matrix; including that proposed by Navick and Furth (1994) for estimating the bus route O-D matrix without using an O-D survey to generate the seed matrix. This work was the basis for the method used to generate the O-D matrices used in this analysis.

Passenger boarding and alighting (on-off) counts are generally available from either manual ride checks or automatic passenger counters. These on and off counts represent respectively the row and column totals of the O-D matrix; however, many possible solutions to the O-D matrix exist given these constraining totals. Furth and Navick present one method for determining the O-D matrix $\{ t_{ij} \}$ that matches the on and off totals where:

t_{ij} = number of trips from origin i to destination j

The method includes:

1) generating a seed matrix
2) estimating the O-D matrix

The seed matrix is generated using a propensity function that models the propensity of travel as a function of distance. When considering round trip travel, the propensity function is equivalent to a gamma function, which is the product of a power term and an exponential. The power term represents the propensity of travel and the exponential represents the decay in the propensity as distance increases. However, in the case of one directional travel the propensity function is just a power function, since although decay in propensity is expected as distance increases, it cannot be identified in the case of one directional travel.

Propensity Function: $p(d_{ij})$

$$p(d_{ij}) = d_{ij}^{\alpha} e^{-d_{ij}\beta}$$

Seed Matrix: s_{ij}

$$s_{ij} = p(d_{ij})$$

The power function parameter, α , was estimated using origin and destination data from bus routes in Boston and Miami and it was found that an α of 1.0 had the best fit across all combinations of routes, days, and times. Statistically it was also determined that an $\alpha = 1.0$ performed better than the null seed where α = zero.

Thus the final seed matrix for one directional travel is simply the distance matrix:

$$\{s_{ij}\} = \{d_{ij}\}$$

The estimation method used by Navick and Furth is the doubly constrained gravity algorithm which is an iterative method. The double constraints are the origin and destination totals. Table 2-1 shows a sample distance matrix, $\{s_{ij}\}$, with the origin and destination (row and column) total on and off counts.

Table 2-1 Sample Distance Matrix $\{s_{ij}\}$

	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7	Stop 8	Stop 9	Stop 10	On
Stop 1		0.1	0.3	0.7	1.6	1.95	2.05	2.6	2.75	3	71
Stop 2			0.2	0.6	1.5	1.85	1.95	2.5	2.65	2.9	125
Stop 3				0.4	1.3	1.65	1.75	2.3	2.45	2.7	20
Stop 4					0.9	1.25	1.35	1.9	2.05	2.3	12
Stop 5						0.35	0.45	1	1.15	1.4	134
Stop 6							0.1	0.65	0.8	1.05	42
Stop 7								0.55	0.7	0.95	115
Stop 8									0.15	0.4	3
Stop 9										0.25	0
Stop 10											
Off		0	1	15	64	28	22	21	120	251	522

The gravity model is as follows:

$$t_{ij} = t_{i}.\frac{X_j s_{ij}}{\sum_{j'} X_{j'} s_{ij'}} \quad \text{for all } i, j$$

where, X_j is an endogenous factor for column j

$t_i.$ is the row total (boardings)

The algorithm begins with X_j equal to $t._j$, the column totals (alightings). The gravity model is applied to generate a trial matrix, which will result in the row totals remaining the same and the column totals changing. The procedure is then iterative and continues to generate a new trial matrix and adjusting all column factors until convergence is reached: the row totals and column totals matching the on-off counts. Table 2-2 shows the final O-D matrix, $\{t_{ij}\}$, estimated from sample distance matrix, $\{s_{ij}\}$, with row and column totals shown in Table 2-1. The row totals are the same as the original totals and column totals are very close but not identical to the original totals due to rounding.

Table 2-2 Sample Estimated O-D Matrix $\{t_{ij}\}$

	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7	Stop 8	Stop 9	Stop 10	On
Stop 1		0	0	6	20	6	4	2	12	21	71
Stop 2			1	9	35	11	7	4	20	38	125
Stop 3				1	6	2	1	1	3	6	20
Stop 4					3	1	2	0	2	4	12
Stop 5						8	7	7	36	76	134
Stop 6							1	2	12	27	42
Stop 7								5	33	77	115
Stop 8									1	2	3
Stop 9										0	0
Stop 10											
Off	0	0	1	16	64	28	22	21	119	251	522

Stop Spacing

Rodriguez (2003) examines BRT, with the goal of evaluating and prioritizing key BRT components including the physical components such as right-of-way priority and expedited boarding. She evaluates these components by considering various decision variables including stop spacing and frequency which are most relevant to the design of limited-stop service. Rodriguez analyzes stop spacing in detail; however, while high frequency is mentioned as a BRT service attribute, it is not analyzed in detail.

The importance of each BRT component or decision variable is assessed through its impacts and implementation costs. The focus is on the user impacts, specifically travel time (access time, wait time, and in-vehicle time), and agency impacts, specifically operating costs (running time) and capital costs (infrastructure and technology). Access time, wait time, in-vehicle time, and operating cost are all affected by limited-stop bus service.

The positive and negative effects of increasing stop spacing are considered including the following positive effects: reduced travel time, reduced dwell time variability, increased ridership due to in vehicle time savings, and reduced running time. The negative effects include: higher mean passenger access time, lower route coverage, and reduced ridership due to lower coverage. After further analysis of stop spacing, the conclusion is drawn that increasing stop spacing will not affect average access time and will not reduce travel time significantly, but will reduce corridor coverage.

This thesis research is in part an extension of Rodriguez work but with one very important difference: the focus will be on the best configuration of two different services along a corridor, rather than on changing to BRT service. In addition, the focus will be on rider choice based on access time, waiting time, and in vehicle time rather than strictly on time and cost savings. Further, the conclusions drawn about stop spacing in the previous paragraph are less binding in the case of the limited-stop and local service overlay since local stop spacing is maintained so that there is no loss of corridor coverage, only a reduction in the frequency for local-only stops.

Furth and Rahbee (2000) present an optimization model using a dynamic programming algorithm to determine optimal bus stop spacing. This is relevant to setting stop spacing on limited-stop routes. The goal of this research was to model the impacts of changing bus stop spacing including:

> In-Vehicle Time increases: more stops increase delays to through riders
> Operating Cost: more stops increase operating cost because of stopping delays
> Walk Time: more stops translate to shorter walking times

Most agencies have stop spacing guidelines, but these policies are not uniform across agencies and are not always followed. It is speculated that the close stop spacing often found in the United States is due to political considerations, i.e. the reluctance of elected officials to eliminate existing stops because of local opposition. One of the observations made about stop spacing from previous studies is that spacing should vary with local conditions, with greater stop spacing on sections of the route with high through volume and low boarding and alighting activity and closer stop spacing where there is lower through volume but higher boarding and alighting activity.

In the Furth and Rahbee paper ridership was held constant, thus ignoring the possible effects on ridership of changing stop spacing. The resulting model determines optimal stop locations and thus optimal stop spacing is a byproduct. Previous models used a continuum approach which only determined optimal stop spacing and left the selection of actual locations to a later stage. The continuum approach has several drawbacks including applying a standard to the actual geography of a route: for example trying to apply a 300 meter stop spacing guideline to a road network where intersections are every 200 meters. Another downside is that the continuum approach models demand as though it were a continuous function, when in actuality demand will be concentrated at specific points.

The Furth and Rahbee model uses a discrete set of all possible stops along the route and then a geographic model is used to distribute demand to the blocks in the route's service area. The assumption underlying the model is that passengers will use the stop that minimizes a weighted sum of their walking and riding time. Stop "shed" lines are identified so that a specific area is tied to a specific stop. Demand data comes from available on-off counts taken aboard buses. The demand was distributed to block faces in the stop's service area based on trip generation density and trip attraction density. This enables demand to be redistributed from existing stops to alternative stops when stops are removed. Walking distance perpendicular to the route is not considered since it is independent of the stop location.

The model takes into account delay at a stop including opening and closing the doors, merging in to traffic, and the delay incurred while decelerating and accelerating; these factors are determined individually for each stop. Also considered is the probability that a bus will actually stop at a particular stop. If the passenger activity component is considered to be a linear function of passengers boarding and alighting and since passenger demand is held constant, the total boarding and alighting time on the route is independent of the stop-spacing and is thus omitted from the formulation.

Waiting Time

Marguier and Ceder (1984) focus on passenger waiting strategies for overlapping bus routes. This is relevant in analyzing the route choice decision made by passengers at a stop with both limited and local service. This paper investigates the route-choice decision for passengers faced with overlapping routes one of which has a lower travel time, using mathematical expressions for passenger waiting time. The first part of the paper focuses on the route choice decision for passengers at a stop served by both routes and the passenger can choose to take the first bus that arrives or wait for a faster bus. The second part focuses on estimating the proportion of passengers that will choose each route.

Three main topics can be included in a probabilistic analysis of waiting time:

1. Bus regularity (headway distribution), which directly affects waiting time
2. Bus arrival variability (between days), which affects the passenger arrival pattern.
3. Passenger arrivals

The main assumptions in this research are:

1. Passengers have some information about both the headway distribution, and the expected in-vehicle time.
2. Passengers are influenced by the amount of time they have already waited.
3. The bus arrival processes of the two routes are independent.

For small headways (less than 3 minutes), buses tend to arrive randomly and for larger headways regularity increases with the headway. The headway distribution belongs to a family of functions which are bounded at one extreme as deterministic and at the other extreme as exponential. Two distributions which have this property are used, one of which is a power distribution, and the other is a gamma distribution. The two distributions are shown for values of C^2, the squared coefficient of variation, ranging between 0 and 1, where 0 corresponds to deterministic headways and 1 corresponds to the completely random case of exponential headways. Based on previous research it appears that the actual distribution is somewhere between the power and gamma distributions: it has a maximum point like the gamma distribution but has a positive intercept as in the power distribution.

The strategy is determined as follows: If route 1 is the faster route, then if the first bus to arrive is a route 1 bus, then the passenger should board that bus, otherwise the strategy will depend on whether the remaining waiting time RW until the next route 1 bus, given that the passenger has already waited a time t_0, plus the in-vehicle time for route 1, t_1, is less than the in-vehicle time for route 2, t_2. The remaining waiting time is a function of the time already waited t_0. This remaining waiting time is shown for various values of C^2 and except in the case of the exponential ($C^2=1$), RW is a decreasing function with respect to t_0 (and is linear in the case of the power distribution).

The second part of the paper discusses the estimation of the share of passengers boarding each route: The share of passengers who take route 2 are determined based on the probability that the first bus to arrive is on route 2 and that the difference between the in-vehicle time for routes 1 and 2 is less than the remaining waiting time for a route 1 bus, given the amount of time that they have already waited. Two variables are defined: the route 2 frequency share, and the ratio of in-vehicle time difference to the headway of the route. The route share is plotted as a function of each of these variables for both the power and gamma distribution. The general conclusion is that the common assumption that the route share is equal to the frequency share is not generally valid. The share of passengers boarding the first bus to arrive on route 2 will increase when the reliability of route 1 decreases (increase in the value of C^2 for route 1) or when the reliability of route 2 increases (decrease in the value of C^2 for route 2).

2.3 Measures For Evaluating Limited-Stop Bus Service

There are four categories of evaluation measures that will be used in this thesis to evaluate a specific service configuration in a corridor having both local and limited-stop service:

1. **Market Share**
2. **Stop and Route Assignment**
3. **Percent Change in Passenger Travel Time**
4. **Productivity**

2.3.1 Market Share

Limited-stop service results in several markets or several passenger categories. An important measure of effectiveness is the percentage of passengers expected to be in each category for a given service configuration. These categories include:

Local Preferred: "Local preferred" riders are passengers who cannot, or will not, walk an additional distance to get to (or from) a stop with both local and limited-stop service at the origin (and/or the destination) of their trip and thus can only take the local service.

Limited Preferred: "Limited preferred" riders are passengers who take the limited-stop service exclusively; these passengers will wait for the limited-stop bus even if the local bus arrives first.

Choice: "Choice" riders are passengers who are either already at a limited service stop or who are willing to walk to a limited service stop; however, once at the limited service stop they will take whichever bus arrives first (local or limited).

A successful limited-stop service configuration will have a high percentage of limited preferred riders since these riders will experience travel time savings, whereas choice riders may experience travel time savings but may also be either neutral or actually experience travel time increases due to increased access time, and finally local preferred riders will experience travel time increases due to increased wait time.

2.3.2 Stop and Route Assignment

Stop Assignment: Some percentage of passengers will remain at local stops while others will either walk (redistribute) to a limited service stop or are already there. The stop assignment predicts the percentages of all passengers who will be at local stops and at limited service stops.

Route Assignment: The route assignment predicts the percentages of all passengers who take the limited-stop service and the local service. Passengers who take the limited-stop service must already be at a limited service stop and thus this is a subset of the passengers at a limited service stop in the stop assignment.

2.3.3 Percent Change in Passenger Travel Time

Travel time related measures are important for evaluating the effectiveness of a limited-stop service configuration. The percent change in passenger travel time (and weighted passenger travel time) is the percent change in person minutes of total travel time (weighted travel time) for a specific limited-stop configuration versus the base case of all local service when there is no existing limited-stop service or versus the existing configuration of limited-stop service. Weighted travel time is the passenger minutes of travel time when access time, wait time, and in-vehicle time are each weighted by the their respective travel time component weights.

An effective limited-stop service should show negative values for the percent change in both the weighted and un-weighted passenger travel times, since this would mean that there are travel time savings. This measure can also be used to compare the relative effectiveness of various configurations.

2.3.4 Productivity

Productivity is an important measure of the effectiveness of a specific limited-stop bus service configuration. There are two proposed measures of productivity:

Average Passengers Per Trip: this is the total number of passengers on the local (limited) route divided by the number of trips for the time period for the local (limited) service. This is a proxy for the peak load on each service; the lower the differential between the two services the greater the effectiveness of the service configuration.

Average Passengers Per Vehicle Hour: this is the total number of passengers on the local (limited) route divided by the number of vehicle hours for the local (limited) route. This is an overall measure of cost effectiveness.

These evaluation measures will be used to evaluate the effectiveness and general viability of limited-stop service on a corridor. For corridors where existing limited-stop service is ineffective it may be possible to reconfigure the service to make it more effective. In other cases, there may be no effective configuration, implying that limited-stop service is inappropriate for that particular corridor.

2.4 Procedures and Experiences in Cities with Limited-Stop Service

This section will cover experiences with limited-stop bus service at New York City Transit and at the Los Angeles County Metropolitan Transit Authority. These cities were selected because both have had significant experience with limited-stop service and both operate many limited-stop routes.

2.4.1 New York City Transit (NYCT)

Silverman (1998, 2003) reviews the experiences of New York City Transit with limited-stop bus service and focuses on the characteristics of limited-stop service and the critical issues and customer responses associated with this type of service. NYCT operates limited-stop routes where high volume local service exists. In fact, when limited-stop service is introduced, it is not as an additional service but rather the existing local resources are divided between the local and limited-stop services. The fare is the same for limited and local service.

While limited stop is an element of Bus Rapid Transit (BRT), it alone does not constitute BRT. While both limited stop service and BRT are intended to increase speed, BRT also includes elements such as dedicated lanes and signal priority which are not necessarily present in limited-stop service. However, NYCT does consider limited-stop the first phase in its plan to implement BRT service in New York City.

In New York City local stop spacing is every two to three blocks (500-750 feet) while limited-stop spacing is eight to ten blocks (1/2 mile), usually at major intersections, and at stops which have particularly high passenger activity. Limited-stop service can operate faster in part because buses can move out of the right traffic lane (where they are often stopped by turning traffic and double-parked vehicles) and into more free-flowing lanes. In addition, buses can travel at higher speed due to the longer distance between stops.

NYCT classifies routes into two categories: feeder and grid. A feeder route is defined here as a route with a terminal that is a high volume trip generator such as a transportation hub or institution such as a hospital. A grid route is a route that has multiple significant trip generators. Feeder routes are often located in areas of lower density and operate at higher speed than grid routes. Grid routes operate in high density areas and at lower speeds. For feeder routes which have both local and limited-stop service, the local service speed averages 9.6 mph and limited-stop 10.9 mph. The comparable figures for grid routes are 6.4 mph for local routes and 7.5mph for limited-stop service.

The first NYCT limited-stop service began operating 30 years ago in Manhattan to address the problem of slow bus travel speed due to traffic congestion. Limited-stop service is less subject to traffic congestion and traffic signal delays due to the reduced number of stops. Currently there are 200 local bus routes in NYC with 35 having limited-stop service, of which 23 operate only during peak hours. In New York City, limited-stop service is considered very beneficial for both the agency and passengers.

Silverman provides a list of corridor and service configuration characteristics under which limited-stop service operates most effectively:

- wide roadways
- roadways with progressive signal timing
- one-half mile spacing between bus stops
- limited-stop should not operate closely parallel to rapid transit routes (there are some exceptions to this rule, such as routes close to rapid transit lines that are at capacity)
- origin-destination data should indicate a large number of longer distance trips

NYC does not have an official policy in terms of route length. Current routes with limited-stop service range in length from 5 to 18 miles and average 8.5 miles (9.8 miles in Manhattan which has the longest routes). The limited-stop service segment often extends farther at the outer ends than the local route on the same corridor. When this is done the limited-stop makes all local stops at the outer ends and the local is effectively "short-turned" to match the higher customer volume on the inner segment.

NYCT guidelines for limited stop service require that passenger volume on the route should be high enough to support a minimum 5-minute combined headway and a 50% frequency split between limited-stop and local service is targeted. The policy is that limited-stop service should not exceed 50% on grid routes or 70% on feeder routes.

Two approaches are discussed for coordinating the scheduling of limited-stop and local service.

- Space each service so that the combined headway is even at one of the following three points:

  - Maximum load point
  - Destination terminal
  - Origin terminal

- Consider them as entirely separate services. In all cases the limited-stop will pass the local at some point so that wait times for a bus at combined stops will not be uniform over a route and time period.

Customers in NYC have responded very favorably to limited-stop service. Some customers object to the longer walk time at one or both ends of their trip, but even customers who board at local stops had favorable impressions of limited-stop service. The introduction of limited-stop service has led to greater market retention for these corridors than in the system as a whole. This is significant since ridership in New York City had been declining for 20 years until the free bus to rail transfers were introduced in July 1997.

Market research has shown that customers perceive the travel time savings on the limited-stop service to be as much as double the actual time savings. In addition, NYCT has found that it is not uncommon for customers to pass up local buses and wait for a limited-stop bus, even though in some cases the savings in in-vehicle travel time may be less than the additional waiting time. After evaluating travel patterns on one of the routes (M15), it was found that the farther customers were traveling, the greater the desire for limited-stop service, so that the proportion of customers on limited-stop buses was larger at the outer portion of the route than in the Midtown CBD portion during the AM peak.

A comparison of speed differentials between local and limited-stop service in different parts of the city concluded that limited-stop services were less effective in low density areas because of lower time savings. It was found that there was a 28% speed differential between local and limited-stop routes in Manhattan where buses generally operate most slowly versus a 10.6% speed differential on Staten Island where buses operate the fastest. An analysis of boarding and alighting patterns showed that dwell times at Manhattan bus stops are longer and buses stop at most or all bus stops, whereas buses on Staten Island and Queens have shorter dwell times and stop at fewer stops, thus reducing the advantage of limited-stop service in those areas.

It is difficult to separate limited-stop revenue from local revenue and thus difficult to measure effectiveness based directly on revenue. However, the increased ridership retention resulting from limited-stop service has clearly increased revenue over time. Limited-stop service also offers a method for increasing service on routes with increased ridership while controlling cost: the speed differential between limited-stop and local is a proxy for operating cost savings. If the limited-stop service can save an amount of time equal to, or greater than, the headway of the local service, this can create a savings of one peak period bus.

In some cases the use of articulated buses makes it infeasible to introduce limited-stop service on a corridor since when articulated buses are introduced frequencies are often slightly reduced which may violate the 5 minute combined headway constraint. However, when limited-stop service is still viable on a route with articulated buses, the combination of the two factors has contributed to very high productivity. Three of the limited-stop routes where articulated buses are used are some of the most productive routes in the NYC Transit system.

The next part of the paper deals with span of service issues. Several categories of limited-stop service exist:

Peak periods; peak direction only

Peak period; bi-directional service

Peak periods and mid-days; bi-directional service

Peak periods, mid-days and evenings; bi-directional service

Weekdays all day and weekends; bi-directional service

In general limited-stop service works better when the span is longer, it is also easier to market and easier for passengers to understand. Very short spans or sporadic service is confusing. Passengers traveling in the peak period are generally more time sensitive, while those traveling in the midday are more likely to be senior citizens or parents with small children for whom mobility is more important than time savings. Another issue affecting span of service is the nature of traffic in the area. If traffic is commercial in nature then congestion may be a problem all day and thus all day service may be appropriate, however if traffic congestion is primarily in the peak period then peak period only service may be more appropriate.

In the past, routes were introduced which were unsuccessful because their span was too short and there were very few trips, thus disrupting even headways with little perceived benefit to passengers. Thus these routes were not well received by passenger and were ultimately changed. Branding is also an issue and New York City has attempted several methods of making limited-stop service more recognizable including electronic destination signs, the use of color to distinguish buses and bus stops, and separate schedules at bus stops.

Some of the areas cited as needing further study are stop-spacing guidelines for limited-stop service, guidelines for establishing the combination of local and limited-stop services, and whether limited-stop service can channel too many customers to the limited-stops resulting in excessive dwell time at each stop.

In an interview conducted at New York Transit's Operations Planning Department (Silverman, Gawkowski, et al.) in December of 2003, the following additional points were made.

- Limited-stop service can help make service more reliable by breaking up bunching.

- Limited-stop has been successful even on corridors with narrow congested streets. Examples include the B6 and B41 bus routes in Brooklyn. This holds true as long as the local bus pulls into the stop so the limited-stop is able to pass.

- New York City has found that sometimes the limited-stop service becomes so popular that dwell times increase substantially due to the high volumes at limited service stops. Since New York City policy is not to increase limited-stop service beyond 50% of the service on a corridor, service can only be added if the overall corridor ridership has increased. This suggests that limited-stop service should in fact be increased beyond 50% of the service on the corridor, and this policy should actually be reviewed since it has not been subjected to serious analysis to date. Instead, the problem of increased dwell time due to high volume is sometimes dealt with by removing limited stops to reduce the overall dwell time on the limited-stop route.

- Some exceptions are made to the 5 minute minimum headway guideline. As an example, in Staten Island, limited-stop schedules are built around the ferry boat schedules which run on 15 to 20 minute headways in the peak.

- Passengers are willing to walk to the limited service stop if they are within one or two stops of a limited service stop. It is also possible to transfer from the local to the limited-stop service and vice versa, in the same direction, taking advantage of the free transfer, but this is not believed to be common behavior.

2.4.2 Los Angeles County Metropolitan Transportation Authority (MTA)

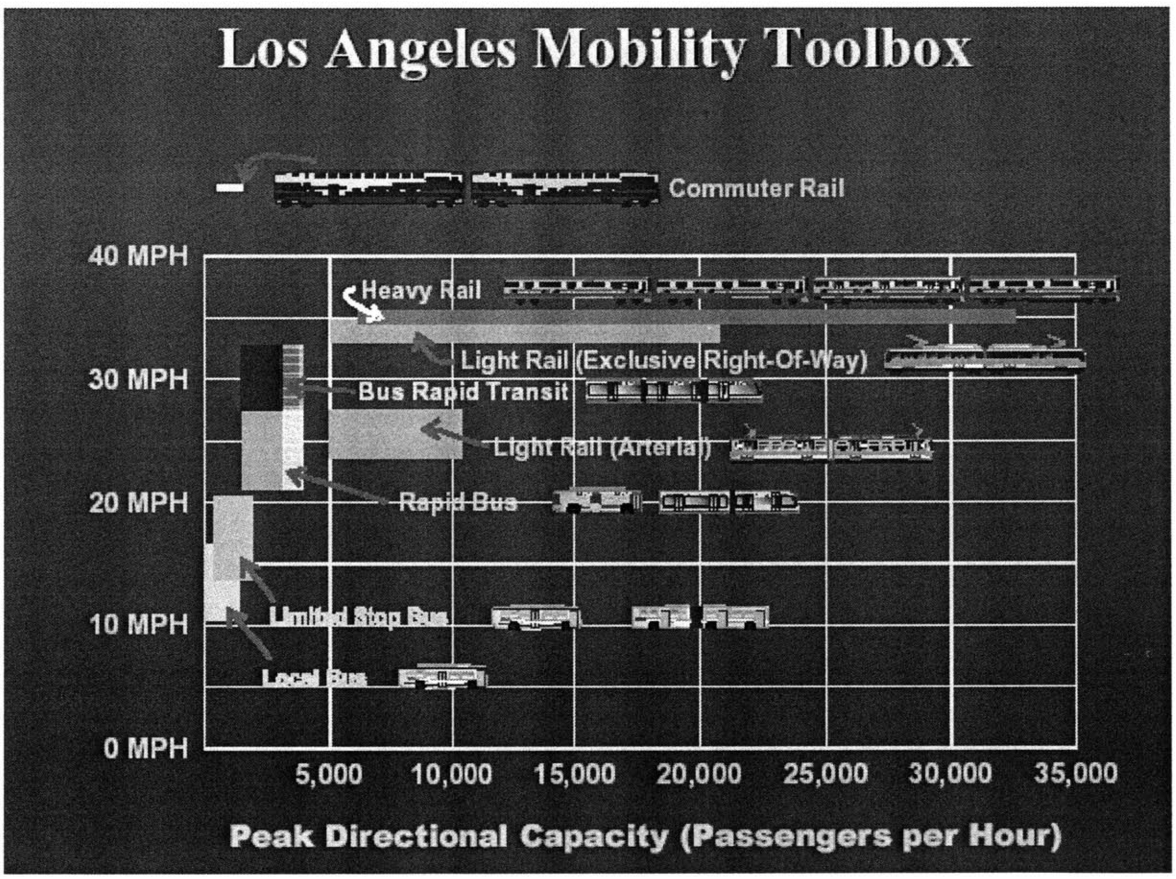
Los Angeles County MTA runs both traditional limited-stop service and BRT type service branded as "Metro Rapid". Metro Rapid was initiated in March of 1999 after an initial feasibility study and now operates on six corridors: Wilshire/Whittier, Ventura, Vermont, South Broadway, Van Nuys, and Florence. Metro Rapid is closer to Bus Rapid Transit than it is to traditional limited-stop service and for some of these routes, specifically Wilshire/Whittier, Metro Rapid service replaced the pre-existing traditional limited-stop service. Metro Rapid has even wider stop spacing than standard limited-stop bus service, operates on a headway based schedule, makes use of branding with color coded buses and stations, and most importantly, makes use of bus signal priority and contributes to reduced running time. Signal priority is not used on local buses (Chapman, 2004). Future phases of Metro Rapid may also include exclusive lanes, high capacity buses, multiple door boarding and alighting, and off-vehicle fare payment. (Gephart, 2004; Transportation Management & Design, Inc., 2002)

MTA operates 22 basic limited-stop routes with many operating only during the peak periods. MTA design guidelines for limited-stop service based on the 2003 Transit Service policy is: "Limited stop service will be provided in local bus corridors where the demand requires service frequencies of 6 minutes or greater. Limited service will make significantly fewer stops than local service, and the key design objective is to operate a minimum of 10% faster than local service" (pp. 6). The frequency criteria is similar to that of New York City which is five minutes or greater.

Based on information provided by MTA, the average stop spacing on MTA routes is 0.2 miles for local service, 0.3 miles for basic limited-stop service, and 0.75 for Metro Rapid. There is only a small differential between the local stop spacing and the limited-stop stop spacing, but clearly there is a significant difference between basic limited-stop service and Metro Rapid. MTA local route stop spacing is wider than at CTA where local stop spacing averages about 0.12 miles; however the stop spacing on MTA limited-stop routes is not as wide as the CTA limited-stop routes which generally have closer to a 0.4 mile average stop spacing.

An interesting finding by LADOT is that 50% of the time that a bus is in service it is stopped and this was part of the motivation behind Metro Rapid (Gephart, 2004). Travel time savings on Metro Rapid routes range from 19 to 29%, depending on the route, and ridership has increased by about 40% on the Wilshire/Whittier and Ventura corridors and one-third of this increase are new transit riders. Figure 2-1 presents the operating speed and capacity for all transit modes in Los Angeles; operating speeds for local service range from about 11 to 16 mph, limited-stop service from 14 to just over 20 mph, and metro rapid from about 21 to 27 mph, so that Metro Rapid time savings are much higher than for standard limited-stop service.

Figure 2-1 LA County MTA Travel Time Savings and Capacity by Transit Mode (Gephart, 2004)



3 EVALUATION OF LIMITED-STOP BUS SERVICE

The previous chapter reviewed the existing literature and prior research related to limited-stop bus service. This chapter will build on that foundation by describing the reasons behind the selection of the model form, presenting the model specification, and finally the limitations of the model.

3.1 Limited-Stop Model Approach

The prior literature and research in this area covers many aspects of limited-stop bus service and will be briefly referenced in this section (see Chapter 2 for a more detailed review). Limited-stop service can be seen as one of several potential cost minimizing strategies; however, research that has addressed limited-stop bus service in the context of other strategies only briefly describes its positive and negative attributes and does not analyze it in depth (Furth, Day, and Attanucci, 1984). Other more specific research on limited-stop service including those of Sholler (2003) and Ercolano (1984), stops short of setting up guidelines governing such important aspects as how to set stop spacing and how to determine the frequency share between local and limited-stop service.

NYCT and the LA MTA both provide basic guidelines for the evaluation of limited-stop routes (Silverman, 2003; LA MTA, 2003), but they do not have detailed and analytically based guidelines on travel time savings, passenger trip length, stop spacing, or frequency share. Both NYCT and the MTA have found that a 50% frequency share can result in overcrowding on the limited-stop route; in response the MTA increased the share of limited trips versus local trips (Chapman, 2004); however, NYCT policy is to maintain a 50% frequency share and thus they have not increased the share of limited-stop service (Silverman, Gawkowski, et al., 2003). Determining the most effective frequency split is an area that needs further research and will be explored in this thesis through the use of the model.

Ercolano (1984) provides suggestions about the travel time savings necessary to create an effective limited-stop service, determining the frequency share between the limited and local service, and recommends analyzing origin and destination data in planning limited-stop bus service. This is also recommended by NYCT (Silverman, 2003). Work done by Navick and Furth (1994) on O-D matrix estimation from boarding and alighting counts makes it feasible to analyze limited-stop service at the origin-destination level and thus the model developed in this thesis will analyze limited-stop service in this manner.

Although comprehensive guidelines for determining limited stop spacing and the frequency split for limited-stop bus service do not exist, there is relevant prior research on stop spacing and frequency. The methodology used by Furth and Rahbee (2000) and by Marguier and Ceder (1984) influenced the form of the model used in this thesis and the method for determining route choice. Furth and Rahbee studied stop spacing and an important underlying assumption in their model is that passengers will minimize a weighted sum of their walking and riding time. Marguier and Ceder studied passenger waiting strategies on overlapping routes where one route is faster; this can be applied to the route choice decision of passengers at limited stops faced with the decision of whether to take the local bus if it arrives first or wait for the limited-stop service. The analysis by Marguier and Ceder assumes that a passenger seeks to minimize total expected travel time and that the passenger will board the first bus that arrives if that bus is faster, but if the first bus to arrive is slower then the passenger will only board the bus if the resulting expected in-vehicle time is less than the expected remaining wait time and in-vehicle time on the faster bus. Thus, in the case of overlapping routes the frequency share for the faster service is a lower bound on the expected route share.

The model design in this thesis assumes that passengers minimize a weighted sum of their expected travel time when they make stop and route choice decisions. The route choice decision was explored by Marguier and Ceder; however, the stop choice decision has not been analyzed explicitly in prior research so this is an important contribution of the model and this research.

3.2 Model Specification

The model created for this research is an evaluation tool which is used to evaluate a specific service configuration. The model calculates travel times and then uses these values to determine the market share and then the stop and route assignment of existing demand. The three market shares are "limited preferred", "local preferred", and "choice" riders; as defined in Chapter 2. The stop assignment is the percentage of total passengers who are either at, or redistribute to, a limited service stop. The route assignment is the percent of total passengers who take the limited-stop service. Finally the model outputs the evaluation measures.

3.2.1 Model Inputs

The key inputs to the model are listed below:

- Resources: This refers to the number of buses that are available to use on the combined local and limited route; this may be either the existing level of resources or increased resources.

- Frequency Share: The frequency share refers to the percentage of total bus trips that are provided on the limited-stop service. This value can range between 0% (all local service) and 100% (all limited-stop service).

- Limited stops: Local stops are assumed fixed as they currently exist, but limited stops are user-defined and are input to the model.

- Headway Distribution: The headway distribution can be deterministic, random, or somewhere in between these two extremes. The model allows for the distribution to be specified for the local, limited, and combined service, depending on the reliability of the specific route. The distribution is specified in the model by specifying the variation in the form of the squared coefficient of variation. The "combined" headway is the expected time between consecutive buses considering both limited and local buses.

- Distance between stops

- O-D demand: The O-D demand matrix is created from on and off counts from either manually or electronically collected data. The procedure for creating the O-D demand matrix is explained in Chapter 2 and is based on the procedure developed by Navick and Furth (1994).

- Local and Limited Running Time: The local service running time is based on observed running time data while the limited-stop service running time is either observed (for existing limited-stop routes) or estimated based on the observed local running time and expected route level running time savings. Limited-stop service running time savings can be estimated by determining the average number of seconds saved per skipped stop based on existing limited-stop routes, calculating the running time savings given the number of skipped stops on the route, and subtracting this value from the local service running time.

- Travel time component weights: Travel time weights are parameters by which each travel time component is multiplied to obtain the perceived travel time. Market research studies have shown that passengers will perceive walk access time, wait time and in-vehicle time differently, thus the model allows different travel time weights to be applied to each of these components. As an example, if a passenger perceives walk access time as three times as onerous as in-vehicle time and wait time as twice as onerous as in-vehicle time, then if the passenger trip requires 2 minutes of access time, 3 minutes of wait time, and 20 minutes of in-vehicle time then this trip which actually takes 25 minutes is evaluated by the model at a value of 32 minutes total perceived travel time.

3.2.2 Travel Time Component Calculations

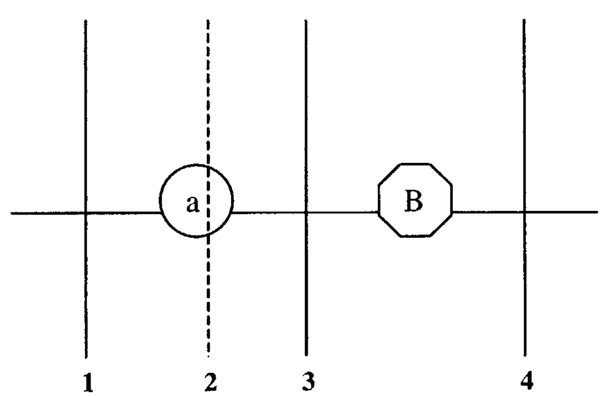
The model uses the inputs to calculate the access time, wait time, and in-vehicle time for each O-D pair. These travel times are then used in modeling market share and stop and route assignment.

Access Time

Access time is determined by multiplying the access distance by the average walk speed which is assumed to be 83 m/min (250 ft/minute) ("Transit Capacity and Quality of Service Manual," 1999). The model does not consider access time to the local stop, since this will not change with changes to the limited stops. For the purpose of this model the quantity of interest is the differential access time for limited-stop service, which is calculated as the distance from the nearest local stop to the nearest limited stop at the origin and/or destination. This is a proxy for the actual access distance differential which is the difference in distances to (from) the actual origin (destination) of each passenger to the limited service stop versus the local stop.

Figure 3-1 presents a diagram to illustrate how access time is calculated and the simplification assumed in the model. The solid lines represent the vicinity of the stop.

Figure 3-1 Access Time



Lines 1 and 3 are the boundary lines for the vicinity of local stop *a*; lines 3 and 4 for limited-service stop *B*. All passengers whose origin (destination) is anywhere within the area bordered by lines 1 and 3 are considered to be within the vicinity of stop *a* and thus the closest stop to their origin (destination) is stop *a*, and similarly for stop *B*. When there is no limited-stop service it is assumed that passengers will board (alight) at the closest stop to their origin (destination). When limited-stop service exists, passengers at some of the local stops will walk an additional distance to a limited service stop. The model calculates the additional access time to the limited service stop as the time it takes to get from the nearest local stop to the nearest limited service stop. Passengers within the vicinity of stop *B* are assumed to have no additional access time since this is their closest stop.

Passengers who begin (end) a trip between the area bounded by lines 1 and 2 and board (alight) at stop *B* will have to walk the entire distance between stop *a* and stop *B*, and thus the model accurately predicts the extra walk distance for these passengers as the distance from the local stop to the limited service stop. Passengers who begin (end) a trip between lines 2 and 3 will have a shorter walk than the full distance since they would not need to pass stop *a* (and these passengers will be more likely to walk to *B* than passenger located between lines 1 and 3), and thus the simplification in the model somewhat overestimates the access time for the passengers who are most likely to make the additional walk to stop *B*. Depending on the actual origins and destinations the estimate may be better or worse, but is generally a reasonable proxy.

Wait Time

The expected wait time is calculated for the limited-stop route, the local route, and for both routes combined based on the headway of each route and the headway distribution using the common expected waiting time equation which is also used by Marguier and Ceder (1984):

$$E(w)=\frac{E(h)}{2}\left[1+c^2\right]$$

Where, w=wait time

h= headway

$c^2 = \dfrac{\mathrm{var}(h)}{(E(h))^2}$, *and where*

$c^2 = 0$, implies deterministic headways

$c^2 = 1$, implies random (exponential) headways

In-Vehicle Time

In-vehicle time is calculated for both the limited-stop and local routes based on average stop-to-stop local and limited run times which are inputs to the model.

3.2.3 Market Classification

Three passenger markets are designated in the assignment: local preferred, limited preferred, and choice riders as defined in Chapter 2. The calculated travel times are used by the model to assign each O-D pair to one of these three market segments. This is an all-or-nothing assignment so that all the O-D demand is assigned to the same market. All-or-nothing assignment is used rather than a logit model because there is insufficient market research available to formulate and estimate a more complex model; it is assumed instead that passengers will try to minimize their perceived travel time which is represented by the total weighted travel time. The model calculates a local preferred, limited preferred, and choice weighted travel time for each O-D pair and classifies each O-D pair based on the lowest weighted travel time.

The local preferred, limited preferred, and choice weighted travel times are calculated as follows:

$$TT_{Loc} = WT_{Loc} * w_{WT} + IVT_{Loc} * w_{IVT} \qquad (3.1)$$

$$TT_{Lim} = AT * w_{AT} + WT_{Lim} * w_{WT} + IVT_{Lim} * w_{IVT} \quad (3.2)$$

$$TT_{Choice} = [AT_{Origin} + (F) * AT_{Dest}] * w_{AT} + WT_{Com} * w_{WT} + [(1\text{-}F) * IVT_{ChoiceLoc} + (F) * IVT_{Lim}] * w_{IVT} \quad (3.3)$$

Where, TT_{Loc}, TT_{Lim}, TT_{Choice} are the total travel times for local preferred, limited preferred, and choice passengers respectively

w_{AT}, w_{WT}, w_{IVT} are the travel time weights for access time, wait time, and in-vehicle time respectively

AT_{Origin}, AT_{Dest}, AT, are the origin, destination, and total access times respectively

WT_{Loc}, WT_{Lim}, WT_{Com} are the local, limited-stop, and combined service expected wait times respectively

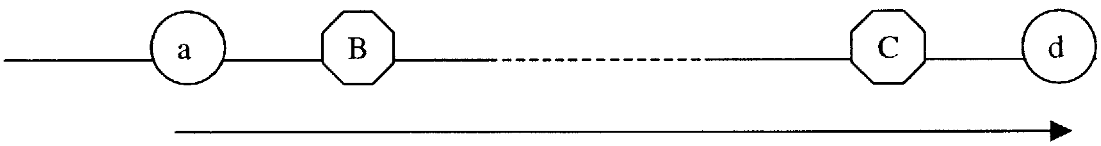
IVT_{Loc}, IVT_{Lim}, $IVT_{ChoiceLoc}$, are the local, limited, and ChoiceLoc in-vehicle times respectively (ChoiceLoc is the in-vehicle time on the local service from the closest limited service stop.)

F, is the limited frequency share

The travel times shown in Equation 3-1, 3-2, and 3-3 are calculated for each O-D pair. The local (limited) travel time is the expected travel time for a specific O-D pair if passengers take the local (limited) service. The choice travel time is the expected travel time for a specific O-D pair if passengers are at, or walk to, a limited service stop and then take the first bus that arrives. Choice passengers only incur additional access time at the destination if the limited-stop service arrives first which occurs a percentage of the time equal to the frequency share, F. The frequency share is also applied to the in-vehicle time, since choice passengers will experience a different in vehicle time (IVT_{Lim} versus $IVT_{ChoiceLoc}$) depending on whether the limited-stop or local service arrives first. The access time is the additional access time from a local stop to the nearest limited service stop and thus there is no access time for the local travel time.

Figure 3-2 provides an example of the market segment assignment for O-D pair *a-d*. Stops *a* and *d* are local stops, while stops *B* and *C* are limited service stops.

Figure 3-2 Market Segment Assignment (Minimum Weighted Travel Time)



Frequency share (F): ~ 60%

	Weights
Access Time	3x
Wait Time	2x
In-Vehicle Time	1x

Service	**Headway (minutes)**	**Variation (c^2)**
Local	15	0.2
Limited-stop	10	0.2
Combined	6	0.7

Travel Times for O-D Pair a-d (time in minutes)	**Local Preferred**	**Limited Preferred**	**Choice**
Access Time – Origin (*a-B*)		2	2
Access Time – Dest. (*C-d*)		1	0.6
Wait Time	9	6	5.1
In-vehicle Time	30	24	26.2*
Total Travel Time	39	33	33.9
Total Weighted Travel Time	48	45	44.2**

*ChoiceLoc In-Vehicle Time: 29.5 minutes (Choice IVT = 29.5 * 0.4 + 24 * 0.6 = 26.2)
**Market segment assignment for O-D Pair a-d: Choice

Local Preferred: 48 = 9*2 +30 *1 *(Equation 3-1)*
Limited Preferred: 45 = (2+1)*3 + 6*2 + 24*1 *(Equation 3-2)*
Choice: 44.2 = [2 + (0.6)*1] * 3 + 5.1 * 2 + [(1-0.6) * 29.5 + (0.6)* 24]*1 *(Equation 3-3)*

The local preferred, limited preferred, and choice travel times are shown. The local preferred travel times are the times if the passenger takes the local service from stops a to d (based on Equation 3-1), while the limited preferred travel times are the times if the passenger takes the limited-stop service from stops B to C, and incurs access time at the origin (a-B) and destination (C-d) (calculated using Equation 3-2). Choice riders may take either the local or the limited-stop service depending on which arrives first and Equation 3-3 is used to calculate the expected travel time. In this example, the choice travel time has the minimum weighted expected travel time and thus all demand is assigned to the choice market segment for this O-D pair.

3.2.4 Stop and Route Assignment

The stop and route assignment are determined as a result of the market classification. Figure 3-3 presents an example including a diagram, a table, and calculations, of how the stop and route assignment can be determined from the market classification.

Figure 3-3 Stop and Route Choice

Frequency share: 60%

	O-D	# of passengers	Market Segment	Stop Assignment	Route Assignment
1	e-G	10	Choice	Limited (F)	Split by Frequency share
2	e-h	10	Local Preferred	Local (e)	Local
3	F-G	10	Limited Preferred	Limited (F)	Limited
4	F-h	10	Local Preferred	Limited (F)	Local

Market Share: *Local Preferred*: 20
Limited Preferred: 10
Choice: 10

Stop Assignment: *Local stop (e)*: 10 passengers (25%)
Limited service stop (F): 30 passengers (75%)
Redistribution (e-F): 10 passengers (25%) [Row 1]

Route Assignment: *Local Route*: 24 (60%) = 20 + 40%*10
Limited Route: 16 (40%)=10 + 60%*10

Stop Assignment

The stop assignment is an all-or-nothing assignment, so all the demand for an O-D pair is assigned to the same stop. The table shows local stops *e* and *h* and limited service stops *F* and *G*. Rows 1 through 4 in the table represent four O-D pairs, the number of passengers traveling between each O-D pair, the market segment, and resulting stop and route assignment. All rows except Row 2 result in a limited service stop assignment. Row 2 is assigned to the local preferred market segment, thus all passenger traveling between this O-D pair are assigned to a local service stop; this is the only situation where passengers will be assigned to a local service stop. Row 1 represents passengers traveling between local stop *e* and limited service stop *G*, and the market assignment for these passengers is choice, therefore the stop assignment is limited and thus these passengers redistribute to limited service stop *F*.

Route Assignment

The route assignment is a product of the market and the stop assignment and is not necessarily an all-or-nothing assignment. Passengers at an O-D pair assigned to the local preferred market (rows 2 and 4) are assigned to the local route, and passengers assigned to the limited preferred market are assigned to the limited-stop route. An O-D pair assigned to the choice market will be assigned to the local or limited-stop route according to the frequency share, and thus an O-D pair that is assigned to the choice market is not an all-or-nothing route assignment. Figure 3-3 also presents the total passengers assigned to each stop and route.

3.2.5 Model Outputs

The model outputs include the measures of effectiveness which are described in detail in Chapter 2. Briefly these measures are:

1. **Market Share**
    - Local preferred

- Limited preferred
- Choice

2. **Stop and Route Assignment**

3. **Percent Change in Passenger Travel Time**
   - Weighted
   - Un-weighted
4. **Productivity**
   - Average Passengers Per Trip
   - Average Passengers Per Vehicle Hour

3.3 Model Limitations

The model developed for this thesis has several limitations.

Demand

The belief that the addition of effective limited-stop bus service will lead to ridership gains is supported by transit agency experience. New York City Transit has found that the introduction of limited-stop bus service has resulted in higher ridership retention on the corridors where it was added than for the system as a whole (Silverman 1998, 2003). Chicago Transit Authority has found that ridership has increased by 3-4% on corridors where limited-stop bus service was added. With the addition of Metro Rapid in Los Angeles ridership increased by over 25% (Gephart, 2004) and while Metro Rapid is not a standard limited-stop service and is closer to BRT than to conventional limited-stop service, some of the increased travel speed and thus some of the increase in ridership can be attributed to the limited-stop component.

The model developed in this thesis is strictly an assignment model and does not predict increases in demand, primarily because there is not enough research available to formulate and estimate a demand model. Thus it is assumed that the limited-stop configuration that maximizes the level of service for existing customers will also maximize ridership gains. The implication, is that a route for which the most effective limited-stop configuration does not show net total passenger travel time savings and is instead essentially neutral may still be an effective limited-stop service since the travel time savings for limited-stop riders may attract additional riders. This ridership increase can come from more than one source including additional trips taken by existing riders due to the addition of limited-stop service as well as trips taken by new riders.

Assignment

The primary assumption in the assignment process is that passengers make decisions based on minimum expected weighted travel time. However, there are several factors which may affect the stop and/or route assignment process when analyzing limited-stop service.

- Weather conditions can affect both the stop and route assignment since passengers may be less willing to walk further to a limited service stop in rainy or very cold weather and more likely to board the first bus to arrive at a limited service stop.

- Availability of shelters at limited stops may affect the route assignment and have a mitigating influence on the effects of weather conditions, since passengers may be more willing to wait in a shelter.

- Real time information may have a significant effect on the route assignment, since if passengers know how long the wait is until the next limited-stop bus then they are more likely to wait for it.

- Lack of awareness about the limited-stop service can affect both the stop and route assignment since passengers will not walk further to a limited service stop or wait for the limited-stop service if they are not aware that limited-stop service exists or are uncertain about the location of limited service stops.

4 MODEL VALIDATION AND APPLICATION

The analysis and evaluation model proposed in Chapter 3 requires one or more transit applications to determine its validity for evaluating limited stop bus services. The CTA's Western Avenue local route 49 and limited-stop route X49 were selected to test the validity of the model and its underlying assumptions. The limited-stop service on Western Avenue was created in 1998 and has been operating longer than any of the other CTA limited-stop routes. This chapter presents both the model validation and the model application; the model application will involve two CTA cases studies: Western Avenue 49 and X49 and a test of the potential improvements to these services and a test of the potential for introducing limited-stop service to the Madison Avenue Route 20 corridor.

4.1 Routes 49 and X49: Western Avenue

There are several CTA bus routes that operate along Western Avenue in Chicago. Routes 49 and X49 are the two primary routes on the corridor and will be the focus of this analysis. Route 49 is the local service on the route and services all local stops while Route X49 is the limited-stop route which services only designated stops.

While Route X49 is a limited-stop route it falls short of full BRT standards in several respects. Signal priority is not currently used and there is no dedicated lane. There is no branding on the limited-stop route, on buses or at stops, and there is no real time next-bus information available at stops, so there is no way for passengers waiting at stops to distinguish in advance which bus is approaching until the bus is at, or very close to, the stop. The operating plan is schedule-based as opposed to the headway-based service used on Metro Rapid in Los Angeles. Finally, fare payment is on-board the bus.

Figure 4-1 shows a map of the route with the demand along the route, for the AM Peak period, represented by boarding and alighting counts at each stop.

Figure 4-1 Route 49/X49 Map

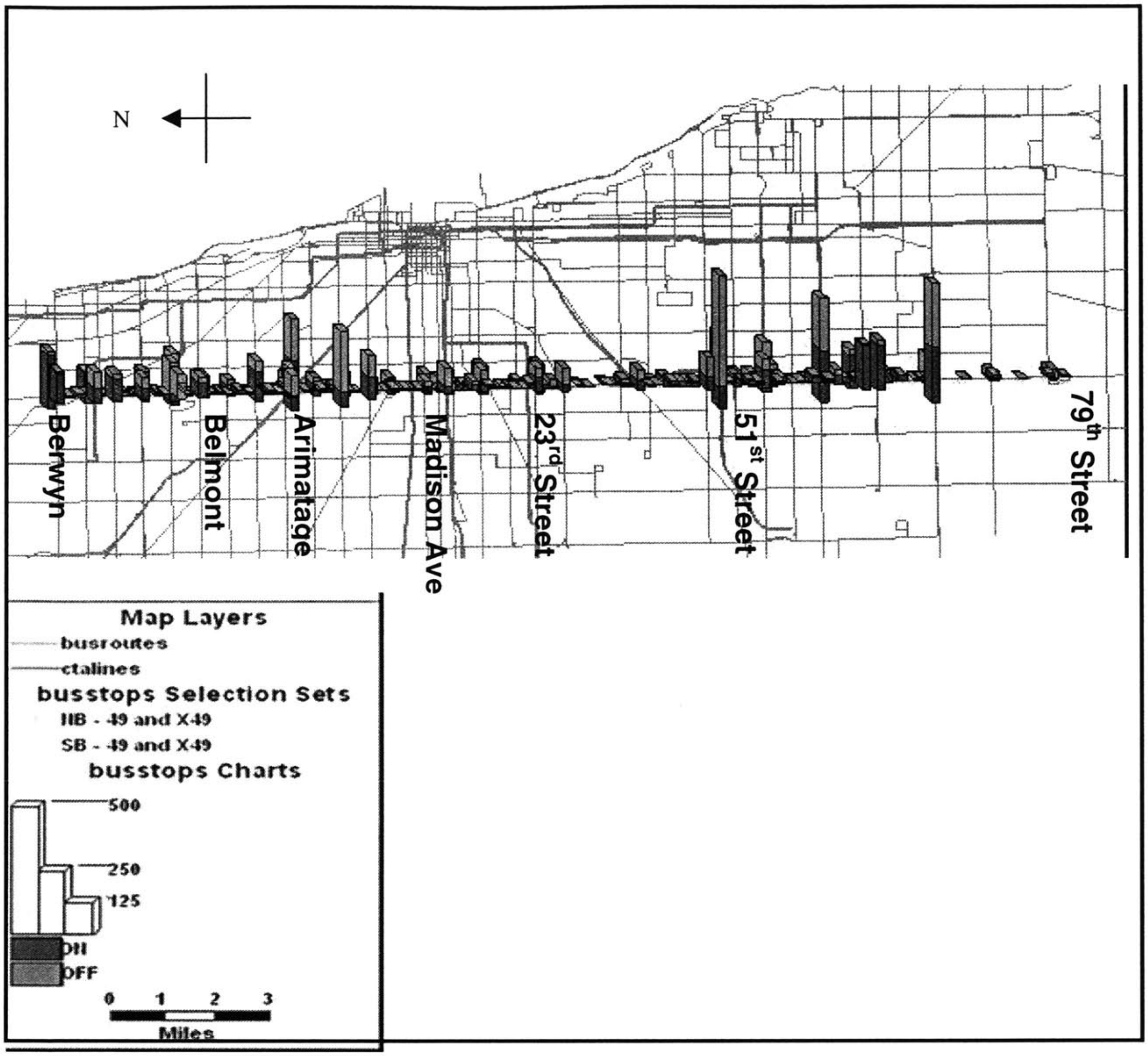


Table 4-1 shows some of the characteristics for routes 49 and X49, including route length, run time, number of stops, stop spacing, and ridership.

Table 4-1 Route 49 and X49 Characteristics

	Route 49	Route X49	Differentials
Route Length (miles)	15.75	18	
Run Time* (minutes)			***Time Reduction***
NB	86	71	17%
SB	85	72	15%
Round Trip	171	143	16%
Vehicle Cycle	195	167	14%
Stops*			***Stop Reduction***
NB	132	37	72%
SB	130	36	72%
Average Stop Spacing* (miles)			
NB	0.12	0.44	
SB	0.12	0.45	
AM Peak (7:00-9:15 AM) Ridership* (passengers)	2725	1235	***Limited share*** 31%

**limited and local overlapping portions only*

Routes 49 and X49 operate along Western Avenue and overlap for approximately 16 miles with Route X49 operating a further 2 miles to the South. Route 49 operates from Berwyn to 79th Street while Route X49 operates from Berwyn to 95th Street, but the analysis will focus only on the overlapping portion of these routes. The number of stops on the X49 represents a 72% reduction over Route 49, and the average stop spacing on Route X49 is 0.45 miles versus 0.12 miles on Route 49. Reducing the number of stops results in a running time reduction of 16% on Route X49 versus Route 49.

This analysis will focus on the AM Peak period, defined here to be 7:00 to 9:15AM. The AM Peak was selected since most trips during this time period are home to work trips and most of these trips recur every day at approximately the same time and with the same O-D pattern and thus ridership patterns are most predictable and stable during this time period. In addition, the AM Peak period generally has the highest ridership and passengers are most time sensitive during this period, thus limited-stop service is most likely to be effective under these conditions. The specific hours were chosen based on ridership patterns on CTA routes and because these hours provide a sufficiently long block of time to obtain a significant level of ridership data by stop.

The total ridership for this time period for the overlapping portion of the two routes is 2725 for Route 49 and 1235 for Route X49. These values are based on a combination of Automatic Passenger Counting (APC) and Automated Fare Collection (AFC) data provided by CTA. The AFC data provides average hourly ridership for a specific month: April 2004. The APC data is based on 10 weekdays of data from April 4 to April 15, 2004 and includes Automated Vehicle Location (AVL) data. Average stop to stop running times are determined based on the AVL data. The APC data was used to establish the demand pattern along the route from boarding and alighting counts, which were scaled using the hourly AFC passenger totals for the time period. The data shows that the ridership share on Route X49 is 31% of the combined ridership on both routes for the time period.

The model evaluates a route based in part on the origin to destination demand pattern, thus the O-D matrix is created as an input to the model from the scaled boarding and alighting counts using the method developed by Navick and Furth (1994) and described in Chapter 2. The northbound and southbound O-D matrices are shown in Appendix I (only the limited service stops are shown). The values in the matrix represent the estimated demand from the origin to the destination for each O-D pair.

Table 4-2 shows additional route 49 and X49 characteristics including resources (number of buses on the route), number of trips, frequency share (percent of total trips that are limited), headway, and headway distribution (reliability of the route in terms of the squared coefficient of variation, c^2).

Table 4-2 Route 49 and Route X49 AM Peak Resources and Headway Characteristics

	Route 49	Route X49	Combined
Resources (buses)	25	16	41
Trips	35	26	61
Frequency Split	0.57	0.43	
Headway (minutes)	7.8	10.2	4.4
Headway Distribution: c^2	0.5	0.2	0.95

The resources on the route were based on the existing schedule: there are, on average, 41 buses used on the route during the AM Peak period, with 25 buses assigned to the local route and 16 buses assigned to the limited-stop route. The resulting frequency share is 43% limited stop service and 57% local service resulting in an expected combined headway of 4.4 minutes, an expected local headway of 7.8 minutes, and an expected limited-stop headway of 10.2 minutes. The headway distributions for the local, limited, and combined services were determined from the AVL data provided by CTA and these result in c^2 equal to 0.5 for the local service, 0.2 for the limited service and close to random or approximately 0.95 for the combined services. The limited headway is higher than the local headway which contributes to the increased reliability of the limited route; in addition since the limited service has fewer stops than the local service it is somewhat less affected by dwell time variability, traffic light delay and traffic congestion and thus is more reliable than the local service.

4.2 Model Validation

The model, as described in Chapter 3, was primarily designed to evaluate a route without existing limited-stop service, which means that the model assumes that there has been no prior redistribution of passengers to limited stops from local stops. This assumption is not true in the case of existing limited-stop service such as CTA Western Avenue routes where some redistribution has already occurred (see Chapter 3, Section 3.2.4). The result of this redistribution is a different observed O-D matrix than the original all local O-D matrix. The matrix that is observed when limited-stop service currently exists, or that is predicted by the model for a limited-stop service configuration, will be referred to as the "redistributed O-D matrix" and the matrix that is observed when there is only local service will be referred to as the "local O-D matrix."

The model was designed to predict the redistributed O-D matrix from the local O-D matrix. However, if a limited-stop service is already in place, there is no simple and reliable method for determining the local O-D matrix from the observed redistributed O-D matrix or observed boarding and alighting counts. In some cases, the boarding and alighting counts, or the local O-D matrix, may be available from a period prior to the addition of limited-stop service, but this is not the case for CTA Western Avenue routes 49 and X49 and thus the local O-D matrix is not available. The model can still be applied to a route with existing limited-stop service where the local O-D matrix is not available, but only to evaluate configurations that do not require the local O-D matrix. Testing alternative stop spacings, or testing a lower frequency share for limited-stop service than the current level would require the local O-D matrix, since these can result in a different redistribution of passengers.

The redistributed O-D matrix can be used to evaluate some aspects of the existing configuration or to evaluate an increased share of limited-stop service. An increased limited frequency share may result in an additional redistribution of passengers to limited stops from local stops, thus it is acceptable to use the redistributed O-D matrix to evaluate the current limited-stop configuration; however all measures of effectiveness involving net changes must be relative to the existing limited service rather than to the hypothetical all-local service.

There are several measures that can be used to validate the model: route assignment, stop assignment, and route productivity. These measures will be presented for the model using several sets of travel time weights (see Chapter 3, Section 3.2.1), and compared with the actual data to test the validity of the model. The base set of travel time weights, seen in Table 4-3 is loosely based on the Chicago Area Transportation Study (CATS), modified slightly by evidence from other cities. Since these parameters represent passenger travel time perceptions, these may be different for limited-stop service than for standard bus service and thus several sets of parameters will be tested to examine the effects on stop and route assignment.

Five sets of travel time weights were tested, as shown in Table 4-3:

Table 4-3 Travel Time Weights

Travel Time Weights		Access Time	Wait Time	In-Vehicle Time
P1	*Base*	3	2	1
P2	*Equal*	1	1	1
P3	*Scaled down*	2	1.5	1
P4	*Wait=Access*	2	2	1
P5	*Wait> Access*	2	3	1

The set of travel time weights identified as P1 are the base case and sets P2 through P5 are alternate sets. Table 4-4 presents the results of the stop and route assignment under each set of weights as a percent of the total ridership on the route during the AM peak period.

Table 4-4 Route and Stop Assignment

Route and Stop Assignment		Passenger redistribution to limited stops (% of total ridership)	Limited route ridership (% of total ridership)
Actual		0.0%	31%
Predicted			
P1	*Base*	1.1%	31%
P2	*Equal*	5.0%	46%
P3	*Scaled down*	1.5%	35%
P4	*Wait=Access*	2.0%	34%
P5	*Wait> Access*	4.5%	35%

The first column in Table 4-4 shows the passenger redistribution to limited stops as a percentage of total ridership for the time period. In this case, this value should be very close to zero because the underlying O-D matrix is based on the existing limited-stop service and already reflects the redistribution of passengers from local to limited stops. Set P2 (equal parameters) results in the highest redistribution of passengers (5%), and P5 in the second highest redistribution (4.5%); this raises a question about both sets of parameters. P1, P3, and P4 all predict values less than or equal to 2.0%, with P1 resulting in the lowest value of 1.1%.

The second column in Table 4-4 presents the route assignment. The actual limited-stop ridership share as a percent of the total is 31%, thus a set of parameters that produces limited-stop ridership that is close to 31% is more credible. The model produces reasonable results when each set of parameters is used with the exception of set P2. This result across quite different sets of parameters is strong evidence of the validity of the model. Set P2 results in a route choice assignment where limited-stop passengers comprise 46% of the total ridership; this value is the furthest from the actual limited-stop share of 31% and over-predicts the limited-stop ridership share by a significant amount and thus P2 can be rejected as a reasonable set of parameters. These results are consistent with *a priori* beliefs backed by various travel time perception studies that passengers do perceive access time, wait time, and in-vehicle time differently and it is not reasonable to assume equal weights for these travel time components. Set P1, the base case set of parameters, actually predicts a ridership share of 31% for the limited-stop service which is equal to the actual value.

Productivity is another important measure used to validate the model and evaluate sets of parameters; it is measured as the average number of passengers per bus trip and per bus hour for each route.

Table 4-5 presents the model results for the productivity of the limited and local routes under each set of parameters. For both productivity measures, parameter set P2 (equal weights) produces results that are the furthest of all the sets from the actual productivities. The remaining sets all produce productivity measures that are reasonable approximations to the actual productivity measures; however, set P1, the base case set of parameters produces productivity measures that are closest to the actual measures.

Table 4-5 Productivity Measures

Productivity: passengers per trip*	**limited route**	**local route**
Actual Performance	**48**	**80**
Predicted		
P1 *Base*	47	78
P2 *Equal*	68	62
P3 *Scaled down*	53	74
P4 *Wait=Access*	50	76
P5 *Wait> Access*	52	74
Productivity: passengers per vehicle hour		
Actual Performance	**34**	**48**
Predicted		
P1 *Base*	34	48
P2 *Equal*	50	38
P3 *Scaled down*	39	46
P4 *Wait=Access*	37	47
P5 *Wait> Access*	38	46

* *trip refers to a one directional trip (not round trip)*

Based on the above analysis, the model does not appear to be extremely sensitive to changes in the parameters, except in the case of equal parameters; however, parameter set P1 results in the best overall fit to the observed performance and so it will be used in the application of the model. Using this parameter set, the market shares for the existing configuration are presented in Table 4-6.

Table 4-6 Route 49 and X49 Existing Service Market Share

	Market Share
Local Preferred	0.31
Limited Preferred	0.03
Choice	0.66

* *Parameter set P1 (access=3, wait=2, in-vehicle=1)*

Under the current configuration, less than 5% of the total riders will always choose the limited-stop service. Limited preferred riders benefit most from limited-stop service: choice riders benefit to a lesser degree, and local preferred riders generally experience higher travel times due to increased wait time for the local service. The success of a limited-stop service is therefore dependent on the number of limited preferred riders and there are very few under the current configuration. In addition, there is a wide differential (1.7) between the local and limited-stop service passengers per trip productivity measures, which implies that the service is not very effective, since an effective limited-stop service will have a lower differential so that overall resources are being used more efficiently.

An effective limited stop service is one which maximizes passenger travel time savings and results in a small differential between local and limited productivity. The next section will consider alternative service configurations to determine if a more effective configuration for Western Avenue limited-stop service exists.

4.3 Application: Western Avenue

The previous section demonstrated that the model is valid and it can now be used to test alternate scenarios for Western Avenue service as the first case study application.

4.3.1 Limited-Stop Service Configurations

Several alternative configurations for Western Avenue service are considered:

- Local stops are fixed, and since the local O-D matrix is not known in this case, alternative stop spacing configurations cannot be analyzed directly with the model.

- The available resources refers to the number of buses that are assigned to the combination of local and limited-stop routes during the AM Peak period; all 49 and X49 configurations that will be evaluated are resource neutral, meaning that it is assumed that there is no increase (decrease) from the resources currently being used on the route. As shown in Table 4-2 (presented earlier) there are currently 41 buses used on Western Avenue for routes 49 and X49.

- The frequency share on the route refers to the percentage of total trips that are limited-stop trips. The current frequency share is 43% limited-stop service (57% local) and increased frequency shares of 50%, 60%, 65%, and 72% limited-stop service will be analyzed. The maximum frequency share analyzed is 72% because this results in a local headway of approximately 15 minutes, and since the combined headway is less than 5 minutes this is likely the highest the local service headway can be set and still be acceptable.

- The local, limited, and combined headways for each limited-stop frequency share are presented in Table 4-7.

Table 4-7 Route 49 and X49 Headways

	Limited-Stop Frequency Share				
Headway	**43%**	**50%**	**60%**	**65%**	**72%**
Local	7.8	8.8	10.8	12.1	14.9
Limited	10.2	8.6	7.1	6.5	5.8
Combined	4.4	4.4	4.3	4.2	4.2

As the limited-stop frequency share increases, the combined headway decreases slightly because the limited-stop cycle time is shorter than the local cycle. Thus one of the advantages of increasing the share of limited-stop service is that there is effectively more total service on the corridor.

- The headway distribution can be deterministic ($c^2 = 0$)[1] so that the expected wait time is half the headway, random ($c^2 = 1$) so that the wait time is equal to the headway, or somewhere in between these two extremes. The headway distribution becomes more variable (increased c^2) as the headway decreases. The limited-stop service is somewhat more reliable at the same headway as the local service since it stops at fewer stops and is thus somewhat less affected by dwell time variability, traffic light delay, and traffic congestion than the local service. Based on the existing limited-stop service configuration, the c^2 estimated from existing AVL data is 0.2 for the limited-stop service, 0.5 for the local service, and very close to 1 for the combined

[1] c^2 is the squared coefficient of variation

services. The c-squared values for the various frequency shares analyzed are estimated based on these values and the respective headways; these values are shown in Table 4-8:

Table 4-8 Route 49 and X49 Headway Variability

	Limited-Stop Frequency Share				
c-squared	**43%**	**50%**	**60%**	**65%**	**72%**
Local	0.5	0.4	0.3	0.2	0
Limited	0.2	0.25	0.35	0.4	0.45
Combined	0.9	0.9	0.9	0.9	0.9

The value of zero for the local service represents an ideal case where the headway distribution is deterministic for a headway of 15 minutes, but in actuality there will likely be some variability and this value will be slightly greater than zero.

4.3.2 Performance

The alternative frequency share configurations were tested using the model with the principal measures of effectiveness being market share, route choice, stop choice, percent change in passenger travel time, and productivity.

Market Share

Table 4-9 shows the estimated market share results for each configuration.

Table 4-9 Route 49/ X49 Market Share Results

	Limited-Stop Frequency Share				
Market Share	**43%**	**50%**	**60%**	**65%**	**72%**
Local Preferred	0.31	0.30	0.26	0.24	0.22
Limited Preferred	0.03	0.17	0.40	0.56	0.64
Choice	0.66	0.53	0.34	0.20	0.14

As expected, the share of limited preferred riders increases as the limited-stop frequency share increases. The greater the number of limited-stop riders, the greater the travel time savings from in-vehicle time savings which results in a more effective overall service configuration. The most important result is the significant increase in the limited preferred market share when the frequency share increases from 50% to 60%.

As the limited-stop frequency share increases there is a greater differential in expected wait time between the limited-stop and local service, resulting in a lower expected wait time on the limited-stop service, thus providing more incentive for riders to wait for the limited service. This lower expected limited wait time combined with the travel time savings on the limited service creates more limited preferred riders and fewer local preferred and choice riders. This is the reason behind the increase in limited preferred riders as limited frequency share increases.

Table 4-10 provides an example of how the frequency share can affect the route choice for a specific O-D pair and a trip of about 2 miles:

Table 4-10 Effect of Frequency Share on Route Choice: Sample O-D Pair, 2 mile trip

(Time in minutes)	**Expected In-Vehicle Time**	**Added Access Time**	**Expected Wait Time**		**Total Weighted Travel Time**	
			43% FS	**65% FS**	**43% FS**	**65% FS**
Local Preferred	15.0	0	5.8	7.3	26.6	29.6
Limited Preferred	12.8	2	6.1	4.4	31.0	27.6
Choice	14.0	2	4.3	4.1	28.6	28.3
Market Assignment*					*local preferred*	*limited preferred*

** Based on lowest weighted travel time*

The expected in-vehicle time and the access time do not change with the frequency share. The expected wait time and the total weighted travel time for 43% and 65% frequency shares (FS) are shown with base travel time weights assumed (1 for in-vehicle time, 2 for wait time, and 3 for access time). For this particular O-D pair with a 43% frequency share, the market assignment is local preferred; however, when the frequency share is increased to 65%, the market assignment is limited preferred. Since wait time is weighted more heavily than in-vehicle time, changes in wait time have a strong effect on the assignment process.

Stop and Route Assignment

Table 4-11 presents the stop and route assignment results for each limited-stop frequency share configuration.

Table 4-11 Route 49/X49 Stop and Route Assignment

	Limited-Stop Frequency Share				
Assignment	**43%**	**50%**	**60%**	**65%**	**72%**
Limited Stop*	0.78	0.79	0.80	0.82	0.84
Limited Route*	0.31	0.44	0.60	0.69	0.74

**Stop choice and route choice as the share of total ridership*

The stop choice is the proportion of total riders who are either already at, or who choose to walk to, a limited service stop. The route choice is the proportion of riders who take the limited-stop service either because they are choice riders who take the first bus to arrive or because they are limited preferred riders. The limited-stop share for both stop and route assignment increases with limited-stop frequency share, but the increase is much more significant for the route than for the stop assignment: there is only minimal additional redistribution of passengers to limited service stops at greater frequency shares.

An increase in the limited frequency share results in some additional redistribution of passengers to limited service stops since the reduced wait time on the limited-stop service combined with the in-vehicle time savings can offset the increased access time to the limited service stop for passengers not already at a limited service stop. This is illustrated in the example shown earlier in Table 4-10: at a 43% frequency share the passenger is a local preferred rider who will choose not to walk to a limited stop; however, at a 65% frequency share the passenger becomes a limited preferred rider prepared to walk the extra distance (redistribute) to the limited stop.

The limited route share increases both because of the increase in limited preferred riders and because more choice riders will board the limited-stop service since there is a higher probability of this service arriving first as limited-stop frequency share increases.

Passenger Travel Time

Table 4-12 shows the percent change in travel time for each frequency share compared with the base frequency share of 43%.

Table 4-12 Route 49/ X49 Percent Change in Passenger Travel Time Results

Percent Change in Total Passenger Travel Time	*Limited-Stop Frequency Share* 50%	60%	65%	72%
Travel Time	-1%	-2%	-3%	-4%
Weighted Travel Time	0%	0%	0%	-2%

The net change in travel time is the percent change between the total person minutes of travel time under the existing configuration of 43% limited service versus another frequency split. Values are shown for both the un-weighted and weighted travel times. There are steadily increasing travel time savings as the limited frequency share increases; however, no weighted travel time savings are apparent until the frequency share increases to 72%. The travel time savings are in-vehicle travel time savings and since access time and wait time are weighted more heavily, a high level of in-vehicle travel time savings must be obtained to counteract the increased access time for limited preferred and choice riders and especially to counteract the increased wait time for local preferred passengers. High numbers of limited preferred riders are needed to obtain significant in-vehicle travel time savings and this number is finally achieved with a 72% frequency share. As discussed in Chapter 3 the model does not predict increases in demand but rather it is assumed that the configuration which maximizes the benefits for existing customers will result in the highest ridership increases. However, a combination of in-vehicle time savings and increasing the frequency on the limited may contribute to attracting new riders.

Productivity Measures

Table 4-13 presents the productivity measures for Western Avenue, for each limited-stop frequency share configuration. Also shown in the table are the number of trips for each service and the number of passengers on each service so that the productivity measures can be more easily understood.

Table 4-13 Route 49/X49 Productivity Results

Productivity	*Limited-Stop Frequency Share* 43%	50%	60%	65%	72%
Trips					
Local Bus	35	31	25	22	18
Limited Bus	26	31	38	41	46
Passengers					
Local Bus	2720	2220	1580	1240	1040
Limited Bus	1240	1740	2390	2720	2930
Vehicles					
Local Bus	25	22	18	16	13
Limited Bus	16	19	23	25	28
Passengers Per Trip					
Local Bus	78	73	63	56	57
Limited Bus	47	55	63	66	63
Passengers per vehicle hour					
Local Bus	48	45	39	34	36
Limited Bus	34	41	46	48	47

Passengers per trip, is a measure of feasibility since it is a proxy for the peak load; the lower the differential in productivity between the two routes, the more effective the route is. If the differential is greater than about 1.5 between the two routes, then the service is very difficult to justify. At 43% limited-stop service frequency share the differential exceeds 1.5 and thus the service at this frequency share is not very effective. The productivity measures improve (lower differential between limited and local routes) when the limited-stop frequency share increases beyond 50%, and while a 60% limited share results in equal productivity, the limited-stop and local productivity differentials for 65% and 72% are still low enough to be considered effective. As the number of trips on the limited-stop service increase, the number of passengers on the limited-stop service also increases, but this is not a linear process and thus overall the productivity measures don't maintain a consistent trend beyond 60%. The results for a 60% frequency share are significant because at lower than 60% the local service is more productive than the limited-stop service, and beyond this point the limited-stop service is more productive than the local service, thus 60% is a break point. Passengers per vehicle hour shows the same trend and also demonstrates that at a 60% limited-stop frequency share the limited-stop service becomes more cost effective (higher productivity) than the local service. This cost effectiveness is significant because this is a benefit to the agency.

4.3.3 Western Avenue Findings

The measures of effectiveness demonstrate that the service is more likely to be effective at a greater frequency share than the current 43%. The market share results show a significant increase in limited preferred riders, the stop and route assignment show increases in passengers at limited service stops and on the limited-stop service, passenger travel time savings increase, and the productivity measures improve with respect to capacity and cost effectiveness as frequency share increases. The recommendation based on these results is to increase the share of limited-stop service on Western Avenue to 60%. This can be done in stages by increasing the frequency share first to 50% and then later to 60% based on observed changes in ridership, or by increasing it directly to 60% from the current 43% frequency share.

4.4 Application: Madison Avenue

CTA is considering adding resource neutral limited-stop service on Madison Avenue, where currently Route 20 is the primary route and there is no existing limited-stop service. In this section, the prospects for limited-stop service in this corridor are analyzed using the model.

4.4.1 Route Characteristics and Limited Stop Service Configurations

Figure 4-2 shows a map of the route with the demand along the route represented by boarding and alighting counts at each stop.

Figure 4-2 Route 20 Map

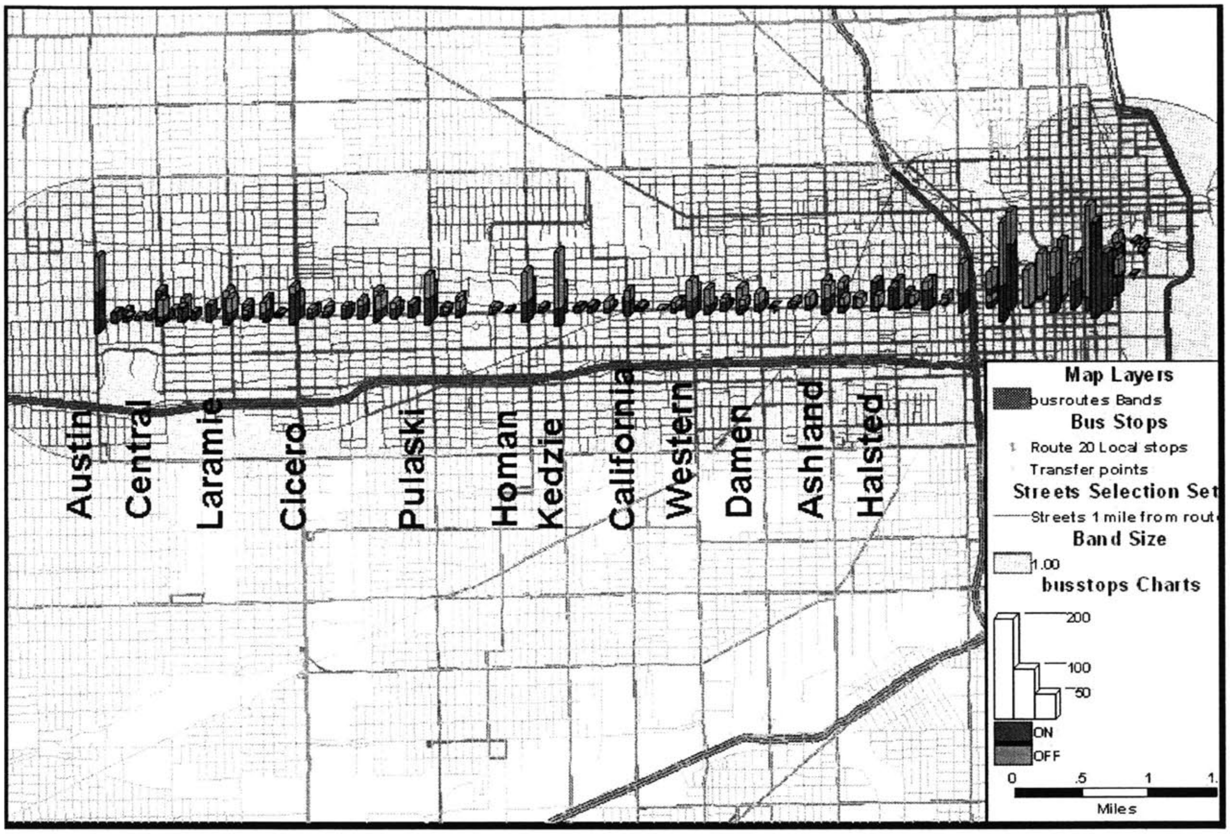


Table 4-14 shows some of the route characteristics for the existing Route 20 and the characteristics of two potential limited-stop route configurations, X20-1 and X20-2 including route length, run time, number of stops, stop spacing, and ridership.

Route 20 operates along Madison Avenue for approximately 8 miles from Austin to Randolph. Two potential limited stop configurations are presented in the table: X20-1, includes a 64% reduction in the number of stops, an estimated 20% reduction in running time, and an 0.38 mile average stop spacing; X20-2, includes a 57% reduction in the number of stops, an estimated 15% reduction in running time, and an 0.3 mile average stop spacing.

Table 4-14 Route 20: Route Characteristics

	Route 20	X20-1	X20-2
Run Time (minutes)			
EB	60	48	51
WB	52	41	44
Round Trip	112	89	95
Vehicle Cycle	126	100	107
Round Trip Time Saved vs. Local		20%	15%
Stops			
EB	67	26	30
WB	63	21	26
Stop Reduction		64%	57%
Average Stop Spacing (miles)			
EB	**0.12**	**0.36**	**0.30**
Austin to Damen	0.12	0.50	0.42
Damen to Columbus	0.12	0.24	0.21
WB	**0.13**	**0.39**	**0.31**
Randolph to Damen	0.13	0.25	0.20
Damen to Austin	0.13	0.56	0.46
AM Peak (7:00-9:15 AM) Ridership (passengers)	3356	3356	3356

Current running times on the route for the local route, boarding and alighting counts, and ridership totals are based on three days of CTA AVL and APC data (November 17-19, 2003). Average local stop-to-stop running times and route level running times are based on the AVL data. The running times for the proposed limited-stop routes are estimated by assuming that every skipped stop results in 14 to 16 seconds of running time savings compared with the existing local stop-to-stop running time. The time savings per stop is based on the running time savings per skipped stop observed on existing CTA limited-stop routes; these range from 9 seconds to 20 seconds and average 15 seconds per stop.

When many stops are skipped, there are likely to be greater time savings per stop than when fewer stops are skipped: when fewer stops are skipped, these skipped stops usually have low demand and are often not serviced by the local buses or have low dwell times when they are serviced, so the savings for these stops is not as great as for higher demand stops. In addition, the eastbound direction is the dominant travel direction in the AM Peak period and skipping stops in this direction is likely to result in more time savings per stop than in the westbound direction. For this reason it was assumed that X20-1, which has the fewest stops will attain on average 16 seconds of running time savings per stop (18 seconds EB, 14 seconds WB) and X20-2 will attain 14 seconds per stop (15 seconds EB, 12 seconds WB). This results in route level running time savings of 20% and 15% respectively for the limited-stop service round trip running time.

The stop spacing on the proposed X20 routes is based on the level of demand at the stops and was selected by adjusting the boarding and alighting count threshold to get two different stop spacing configurations, with successively closer stop spacing. X20-1 and X20-2 both include all transfer points along the route. The O-D matrix is created as an input to the model from the APC boarding and alighting counts using the method developed by Navick and Furth (1994) and described in Chapter 2. The O-D matrix for the eastbound direction showing just X20-2 stops appears in Appendix I. Since there is currently no limited service on the route, the original O-D matrix is available which makes it possible to test limited stop spacing configurations as well as alternative frequency shares.

Table 4-15 shows additional route 20 characteristics including resources, headway, and headway distribution.

Table 4-15 Route 20: Resources, Headway, Headway Distribution

	Route 20
Resources (buses)	23
Headway* (minutes)	5.5
Headway Distribution: c^2	0.5

**average for the time period*

The resources on the route were determined based on the existing schedule: there are, on average, 23 buses used on the route during the AM Peak period, which results in an average headway during the time period of 5.5 minutes (the range is 4 to 6 minutes). All Route 20 configurations that will be evaluated are resource neutral. The headway distribution for the local route based on the AVL data is halfway between deterministic and random with c^2 equal to 0.5.

Several limited frequency share configurations will be evaluated for route 20: 50%, 60%, and 65%. The frequency shares are approximate shares because resources can only be divided in whole units (buses). The headways are shown in Table 4-16 for X20-1 and are similar for the X20-2.

Table 4-16 Route 20 Headways (X20-1)

	Limited-Stop Frequency Share		
Headway	**50%**	**60%**	**65%**
Current		5.5	
Local	9.7	11.5	12.6
Limited	9.1	7.7	7.2
combined	4.7	4.6	4.6

The headway distributions for each of these configurations are estimated based on the headways for each service and the current headway distribution. Table 4-17 shows the headway distribution for configuration X20-1.

Table 4-17 Route 20 Headway Distribution (X20-1)

	Limited-Stop Frequency Share		
c-squared	**50%**	**60%**	**65%**
Current		0.5	
local	0.3	0.25	0.2
limited	0.2	0.3	0.3
combined	0.9	0.9	0.9

4.4.2 Performance

The evaluation for Route 20 involves both changes in frequency and changes in stop spacing. All results presented for route 20 are for the eastbound (EB) direction during the AM Peak, since this is the dominant direction of flow during the time period.

Stop Spacing

The first part of the analysis for Madison Avenue will focus on stop spacing. Table 4-18 presents the standard evaluation measures for the two potential stop spacing configurations, X20-1 and X20-2 with a limited-stop frequency share of 65%. These configurations will be referred to as "C1" and "C2" instead of "configuration X20-1" and "configuration X20-2" for ease of reference.

Table 4-18 Stop Spacing Configuration Results

65% Frequency Share	*Stop Spacing*	
Measures of Effectiveness	**X20-1/ C1**	**X20-2/ C2**
Market Share		
Local Preferred	0.45	0.30
Limited Preferred	0.30	0.47
Choice	0.25	0.23
Assignment		
Limited Stop	0.60	0.73
Limited Route	0.46	0.62
Percent Change in Passenger Travel Time		
Travel Time vs. all local	3%	1%
Weighted Time vs. all local	15%	11%
Trips		
Local Route	11	10
Limited Route	19	19
Productivity: Average Passengers Per Trip		
Local Route	89	69
Limited Route	43	59
Productivity: Passengers Per Vehicle Hour		
Local Route	80	62
Limited Route	48	65

Market Share

C2 results in a higher percentage of limited preferred riders than C1 and lower percentages of both local preferred and choice riders. The greater the number of limited preferred riders, the more effective the service is; these results suggest that, for this route, the configuration with more stops and a shorter spacing results in more effective service.

Stop and Route Assignment

The next evaluation measures are the stop and route assignment. The results show that C2 produces both a higher percentage of passengers at limited service stops and on the limited route than C1. The higher percentage of total passengers at limited stops for C2 is a direct consequence of the increased number of limited stops under C2, so that all passengers at these additional stops are at limited stops under C2 but are at local stops under C1.

The stop assignment is a combination of the number of passengers already at limited service stops and the number of passengers who redistribute to limited service stops. A breakdown of the stop assignment is shown in Table 4-19. The table shows that a higher percentage of passengers are both already at limited service stops and redistributed to limited service stops under C2 than under C1. The redistribution is a function of the assignment process and C2 results in a greater redistribution in part because the distances between limited stops are shorter in this configuration and thus access times are generally shorter which will induce more redistribution to limited stops than under C1.

Table 4-19 Route 20 Stop Spacing Passenger Redistribution

	Stop Spacing	
Passenger Distribution at Stops*	**X20-1**	**X20-2**
Passengers at limited stops	49%	58%
Passenger redistributing to limited stops	11%	15%

* *percent of total passengers*

Passenger Travel Time

The net change in total travel time and the net change in weighted travel time are both positive for C1 and C2, which means that both configurations of limited stop service result in overall travel time increases over the local service. However, there is less of an increase for C2 than for C1.

Productivity

The final measures presented are the productivity measures and once again C2 appears to result in more effective service than C1 because the differential between the passengers per trip productivity measures for C1 are very high, in fact the local productivity is more than twice the limited-stop productivity, and thus it is questionable if this configuration is viable. On the other hand there is a lower differential between the local and limited-stop service productivity measures for C2, which implies that this service configuration is more effective.

All of the productivity measures demonstrate that C2 is more effective than C1 so all limited frequency share analysis on route 20 will use the X20-2 configuration, referred to as C2.

Frequency Share

The limited frequency shares evaluated are 50, 60, and 65%.

Market Share

Table 4-20 presents the predicted market share figures at each frequency share level.

Table 4-20 Route 20 Market Share

	Limited-Stop Frequency Share		
Market Share	**50%**	**60%**	**65%**
Local Preferred	0.42	0.34	0.30
Limited Preferred	0.02	0.27	0.47
Choice	0.56	0.39	0.23

The result observed is similar to the result for the Western Avenue routes: there is a significant increase in limited preferred riders when the limited frequency share increases from 50 to 65%. However, the limited preferred market shares are substantially lower for limited-stop service on route 20 than they were on Route 49/X49, which is an indication that limited-stop service on Madison Avenue may not be effective. These results, combined with the results for the Western Avenue routes demonstrate that limited preferred riders increase with increased limited-stop frequency share and this contributes to more effective service.

Stop and Route Assignment

Table 4-21 presents the results of the stop and route assignment for each limited-stop frequency share.

Table 4-21 Route 20 Model Results: Stop and Route Assignment

	Limited-Stop Frequency Share		
Assignment	**50%**	**60%**	**65%**
Limited Stop	0.61	0.69	0.73
Limited Route	0.30	0.52	0.62

**Stop choice and route choice as the share of total ridership*

As was seen in the results of the Western Avenue evaluation the most important result in the table above is the significant increase in the limited-stop route ridership when the limited frequency share increases from 50% to 65%. Combining this result with the Western Avenue result demonstrates that limited-stop route ridership increases with increasing limited-stop service frequency share, and contributes to a more effective service configuration.

Passenger Travel Time

Table 4-22 presents the net passenger travel times for each limited-stop frequency share.

Table 4-22 Route 20 Percent Change in Passenger Travel Time

	Limited-Stop Frequency Share		
Net Change in Passenger Travel Time	**50%**	**60%**	**65%**
Travel Time	5%	3%	1%
Weighted Travel Time	14%	13%	10%

** net change passenger minutes versus all local service*

The net change in passenger travel time and the net change in weighted passenger travel time results are all positive, meaning that there is an increase in net passenger travel times over the existing all-local service, especially weighted travel time. This is further evidence that limited-stop service may not be effective on Madison Avenue. However, these times decrease with increasing limited-stop frequency share and this improvement is consistent with the results seen for the Western Avenue routes. The implication is that passenger travel times decrease with increasing frequency share.

Table 4-23 shows net passenger travel time in total passenger minutes versus the existing all local service as limited stop frequency share increases from 50 to 60%.

Table 4-23 Route 20 Passenger Travel Time by Travel Time Component

(Time in minutes)	*Limited-Stop Frequency Share*	
Net Travel Time vs. All Local	**50%**	**60%**
Access Time*	260	690
Wait Time*	2880	3070
In-Vehicle Time*	-1450	-2820
Total Net Travel Time	1690	940
Total Net Weighted Travel Time	5090	5390

* *un-weighted*

The results show that there are in-vehicle time savings (negative values for net in-vehicle time) which increase with the frequency share, but access time and wait time both increase and thus both the total net travel time and net weighted travel time increase as seen in Table 4-23.

It is expected that an effective limited service should show travel time savings over all local service, however the results in this case show travel time increases. While limited-stop preferred passengers and some choice passengers benefit through in-vehicle time savings, this is more than offset by the increased wait times for local passengers which is weighted more heavily than in-vehicle time. However, the in-vehicle time savings are present and should not be overlooked since these time savings have the potential to attract additional passengers.

Productivity

Table 4-24 presents the productivity measures for each limited-stop frequency share.

Table 4-24 Route 20 Productivity Results

	Limited-Stop Frequency Share		
Productivity: Average Passengers Per Trip	**50%**	**60%**	**65%**
Local Route	89	80	69
Limited Route	39	52	59
Productivity: Passengers Per Vehicle Hour			
Local Route	79	72	62
Limited Route	43	58	65

The productivity measures for a 50% limited frequency share indicate that the service is not effective based on both capacity and cost effectiveness so it would be very difficult to justify this configuration of limited-stop service. The measures show that the service is still not very effective at 60% frequency share but becomes more effective with a 65% frequency share.

4.4.3 Madison Avenue Conclusions

The analysis of Madison Avenue focused on stop spacing and frequency configurations.

Stop Spacing

The conclusion reached after the stop spacing analysis is that C2 is the more effective of the two limited-stop configurations considered. It has a greater share of limited preferred riders, a higher share of passengers at limited service stops and on the limited route, lower net passenger travel time increases (although not travel time savings), and improved productivity measures. However, lack of travel time savings for C2 is a clear indication that limited-stop service will not be effective on Madision Avenue. This is principally due to the relatively short trip lengths on this route. Shorter trip lengths result in reduced in-vehicle time savings that cannot counteract the higher access times resulting from greater stop spacing, especially since access time is seen as three times more onerous than in-vehicle time. In addition, demand is not concentrated at a small number of stops on Route 20 so greater stop spacing results in a lower percentage of passengers already at limited service stops, so there are more passengers who would be subject to additional access time if they chose to take the limited-stop service. The effect of the demand pattern including passenger trip lengths on the effectiveness of a route configuration will be covered in more detail later in this chapter.

Frequency Share

The analysis of frequency share showed results similar to Route 49/X49: limited preferred riders, passengers at limited service stops and on the limited-stop service all increase with limited-stop frequency share and travel time and productivity measures also improve. However, Route 49/X49 is clearly more effective than Route 20/X20-2 when market share, stop and route assignment, and passenger travel times are considered. In fact, the analysis on Madison Avenue frequency configurations never produces net passenger travel time savings, although it does result in in-vehicle time savings. The productivity measures show that service on Route 20 is not effective at all at frequency shares less than 65% and the travel time results indicate that it is not effective even at greater frequency share.

Conclusions and Recommendations

The analysis shows that that limited-stop service will not be effective in any configuration on Madison Avenue and thus adding limited-stop service on Madison Avenue is not recommended. It may however still make sense to increase stop spacing slightly on the local route, if this is possible. The reasons for the lack of effectiveness will be explored in the next section.

4.5 Demand Pattern Analysis

This section will focus on the effects of the demand pattern on the effectiveness of limited-stop service. The demand pattern includes passenger trip lengths and the distribution of passenger origins and destinations. Passenger trip length can affect the in-vehicle time savings as well as the stop and route level assignment. Limited-stop service will be most effective on a route where many passengers board and alight at limited stops and even allowing some redistribution of passengers the concentration of passengers at limited service stops is critical to the effectiveness of limited-stop service.

4.5.1 Passenger Trip Length

The first part of this analysis will consider the trip lengths on Western Avenue and on Madison Avenue.

Table 4-25 shows the percent of total trips greater than two miles and five miles for routes 20 and 49/X49. Route 49 and X49 have a greater proportion of longer trips than Route 20, which is expected since they are significantly longer than route 20. Route 20 trip lengths are especially short in the westbound direction in the AM Peak period. There is a significant difference in trip length distribution between route 20 and route 49/X49.

Table 4-25 Passenger Trip Lengths (AM Peak)

Passenger Trip Length		> 2 miles	> 5 miles
Route 20	EB	0.42	0.05
	WB	0.14	0.00
Route 49, Route X49	NB	0.54	0.14
	SB	0.57	0.10

**table shows percent of total trips greater than a specific distance*

Route X49 has a stop spacing configuration which more closely resembles C1, the longer stop spacing configuration on Madison Avenue, and Route X49 is effective at this stop spacing. The relationship between passenger trip lengths and stop spacing is explored by replacing the existing route 20 demand pattern with demand patterns that have longer passenger trip lengths, but have the same percentage of passengers who are already at limited stops or traveling to limited stops. The percentage of passengers already at limited stops is 48% for C1, and 58% for C2.

Table 4-26 shows the results for the existing trip length pattern (40% of total trips greater than 2 miles, 5% of trips greater than 5 miles) for the wider stop spacing configuration, C1, and 3 additional trip length patterns.

Table 4-26 Route 20 Passenger Trip Length Analysis (AM Peak)

	X20-1 EB	60% Limited-Stop Frequency Share		
Passenger Trip Length (% of total trips)	*40% > 2mi 5% > 5 mi*	***60% > 2 mi*** *5% > 5 mi*	*60% > 2 mi* ***10% >5 mi***	*60% > 2 mi* ***20% >5 mi***
Market Share				
Local Preferred	0.46	0.45	0.44	0.41
Limited Preferred	0.26	0.30	0.32	0.34
Choice	0.28	0.25	0.25	0.25
Assignment				
Limited Stop	0.58	0.58	0.60	0.63
Limited Route	0.42	0.45	0.46	0.49
Percent Change in Passenger Travel Time				
Travel Time vs. all local	3%	2%	1%	-1%
Weighted Time vs. all local	14%	14%	13%	12%
Productivity: Average Passengers per trip				
Local Route	87	83	81	77
Limited Route	43	45	47	49
Productivity: Passengers Per Vehicle Hour				
Local Route	77	74	72	69
Limited Route	48	50	52	55

All of these results are for the AM Peak period, in the eastbound direction, for a 60% limited-stop frequency split. For C1 the percentage of limited preferred passengers, limited route ridership, and the percent of passengers at limited service stops increase with trip lengths. Percent change in passenger travel time measures show increased travel time versus all local service in all cases except one; however, the increase is less as trip lengths increase. The productivity measures also show some improvement as trip lengths increase since the differential between the limited and local service passengers per trip narrows. These results demonstrate two points: the first is that if there are longer trips on a route the effectiveness will improve; however, these effects are not enough to make the Madison Avenue service effective even at the longest trip lengths. This implies that there are other factors that contribute to the effectiveness of a limited-stop route such as the concentration of origins and destination which will be explored next.

4.5.2 O-D Concentration

It appears from the analysis in this thesis and from prior information on the topic that passengers will not be shifted by more than one or two stops at the beginning and end of a trip even for long trips. We define the O-D concentration as the percentage of trips that begin and end, at or near, a limited service stop. To determine this percentage it was assumed that this is equivalent to the percentage of trips that require 3 minutes or less of additional access time. Since access time is viewed as three times as onerous as in-vehicle time, three minutes of access time is equivalent to 9 minutes of in-vehicle time and even the in-vehicle time savings resulting from long trips will not be able to offset such significant increases in access time. Table 4-27 presents the percentage of trips that begin and end at or near a limited service stop.

Table 4-27 Passenger Trip Concentration

Configuration ***Direction***	**X20-1** **EB**	**X20-1** **WB**	**X20-2** **EB**	**X20-2** **WB**	**Western**
O-D Concentration*	0.60	0.65	0.80	0.80	0.80

**percent of trips that begin and end, at or near, a limited service stop*

For configuration X20-1 about 60% of passengers fall into this category, so this is approximately the maximum number of passenger who could potentially be either limited preferred or choice riders at any limited-stop frequency share; this percentage is much lower than for Western Avenue and for the X20-2 configuration. The percentage is higher for Western Avenue because the O-D concentration is highly concentrated around limited service stops while the high percentage obtained for configuration X20-2 is a result of increasing the number of limited service stops so that more passengers are at, or near, limited service stops.

Table 4-28 presents the results of further analysis when Madison Avenue configuration X20-1 (C1) is considered at 60% limited frequency share for the eastbound direction for the AM Peak period. The first column shows the results of the existing O-D demand pattern with respect to passenger trip length and O-D concentration, the second column shows the results when only the passenger trip lengths are changed, the third column shows the results when only the O-D concentration is changed, and the last column shows changes to both passenger trip length and O-D concentration.

Table 4-28 O-D Concentration and Passenger Trip Length (AM Peak)

	X20-1 EB	60% Limited-Stop Frequency Share		
*O-D concentration**	*60%*	*60%*	***75%***	***75%***
Passenger Trip Length (% of total trips)	*40% > 2mi 5% > 5 mi*	***60% > 2 mi 20% >5 mi***	*40% > 2mi 5% > 5 mi*	***60% > 2 mi 20% >5 mi***
Market Share				
Local Preferred	0.46	0.41	0.31	0.31
Limited Preferred	0.26	0.34	0.34	0.51
Choice	0.28	0.25	0.35	0.17
Assignment				
Limited Stop	0.58	0.63	0.72	0.75
Limited Route	0.42	0.49	0.55	0.62
Percent Change in Passenger Travel Time				
Travel Time vs. all local	3%	-1%	-2%	-9%
Weighted Time vs. all local	14%	12%	10%	4%
Productivity: Average Passengers per trip				
Local Route	87	77	68	58
Limited Route	43	49	55	62
Productivity: Passengers per vehicle hour				
Local Route	77	69	61	52
Limited Route	48	55	61	69

**percent of total trips that begin and end at or near a limited service stop*

A greater O-D concentration results in higher limited-stop route ridership than the longer passenger trip pattern analyzed; however, these extra passengers are choice riders rather than limited preferred, in fact both result in the same percentage of limited preferred riders. This result demonstrates that both trip lengths and the O-D concentration have a strong impact on the share of limited preferred riders. The results presented in the last column demonstrate that the route is most effective when there is a combination of longer trips and a high O-D concentration since this results in the greatest number of limited preferred riders and the lowest differential between the local and limited-stop productivity. There are also passenger travel time savings of 9% which is due to in-vehicle time savings and although the weighted passenger travel times still show increases, these are much lower than the original configuration and are due to increased wait time for local preferred riders and the higher travel time weight applied to wait time.

4.5.3 Demand Pattern Conclusions

Long passenger trip lengths and high O-D concentration both contribute to more effective limited-stop service and both are needed for a route to be highly effective. Madison Avenue is not a good candidate for limited-stop service because passenger trip lengths are too short and because the O-D concentration is too low. Western Avenue is a good candidate because trips are long enough to achieve high percentages of limited preferred riders, and because the O-D concentration is high.

Chapter 5 will extend the results in this chapter to create guidelines for the evaluation and design of limited-stop service.

5 LIMITED-STOP GUIDELINES

The previous chapter presented the validation of the model and the applications to the CTA Western Avenue and Madison Avenue bus services. This chapter will generalize these results and propose guidelines for introducing limited-stop bus service. The model played a key role in the development of these guidelines with various configurations of limited-stop service being evaluated as well as sensitivity testing using the model. The purpose of the evaluation and testing is to understand the effects of different service elements in different operational settings. These elements include corridor characteristics and design elements. The corridor characteristics are the ridership/existing headway, passenger trip lengths, demand concentration, and running time savings potential; the design elements are stop spacing/stop reduction, running time savings, limited-stop frequency share.

Underlying the guidelines are several principals based on model application (Chapter 4) and the previous work in this area (Chapter 2).

- In order for limited-stop service to be effective there must be a high percentage of limited preferred riders.

- There are two general situations where limited-stop service is desirable. The first is when there are two distinct markets such that some passengers are better served by the local service and the rest are better served by the limited-stop service; the second is when the agency wants to reduce stop spacing but for political reasons low demand stops cannot be eliminated, then limited-stop service with greater stop spacing can be run as the primary service but the local service can be maintained at a higher clock-face headway.

- Based on the analysis in Chapter 4 both long passenger trips and concentrated origins and destinations are necessary conditions for highly effective limited-stop service.

Longer passenger trips will result in a higher share of limited preferred riders. Passengers are not willing to be shifted more than one or two stops at the beginning and end of a trip, thus concentrated origins and destinations are necessary to create a large number of potential limited-stop route riders.

- Running time savings must be significant so passengers save enough travel time so that they are willing to walk to limited service stops and wait for the limited-stop service. These travel time savings are obtained primarily though stop reduction and are affected by traffic congestion and traffic signal delays.

- It is clear from Chapter 4 that limited-stop service is most effective when the limited-stop frequency share is greater than or equal to 60% so as to maximize the number of limited preferred riders. This in turn results in the greatest level of passenger travel time savings, which is a primary goal of limited-stop service.

5.1 Corridor Potential for Limited-Stop Service

This section will propose guidelines for evaluating whether a particular corridor is a promising candidate for the introduction of limited-stop service. These guidelines will cover ridership/existing headway, passenger trip lengths, demand concentration, and running time savings potential.

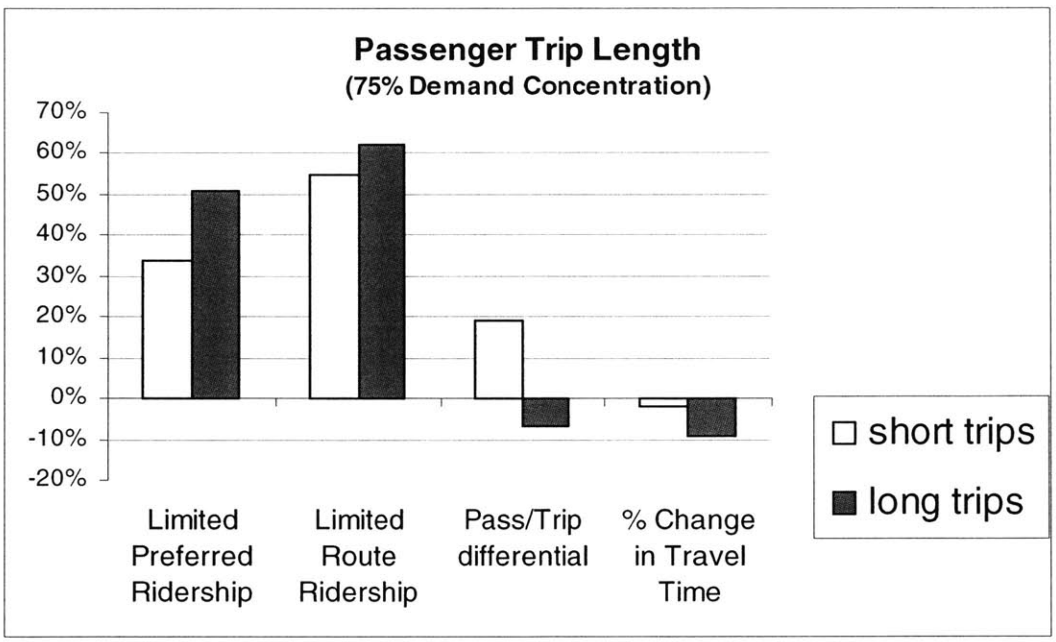
Ridership/Existing Headway

Total demand on a route is an important indicator of whether limited-stop service is likely to be viable on a route. In general, in order for a route to be considered for limited-stop service, it should have an existing headway of no more than seven minutes and preferably five minutes or less. At headways greater than seven minutes, creating a resource neutral limited stop service by splitting the existing local service resources will create high headways on both the local and limited-stop service and is not recommended. Ideally the limited-stop headway should be no greater than 10 minutes: otherwise the limited preferred market will be very small or non-existent.

Passenger Trip Length

Longer passenger trips will increase the likelihood of effective limited-stop service, although this criteria alone cannot guarantee success. Figure 5-1 shows results from the passenger trip length analysis (Chapter 4) assuming a demand concentration of 75%. Long trip lengths in this case refer to a corridor where 60% of trips are greater than two miles, and 20% are greater than 5 miles versus short trips (40% greater than 2 miles and 5% greater than 5 miles). Longer trips result in improved performance for all measures of effectiveness.

Figure 5-1 Effect of Passenger Trip Length on Performance



** Pass/Trip differential: percent difference in limited over local, negative values imply higher limited productivity than local*

*** % change in Travel Time (un-weighted): negative (positive) values imply travel time savings (increases)*

In general, a route where at least 60% of all trips are greater than 2 miles, and where at least 10% of all trips are greater than 5 miles would constitute a route with long trips and is more likely to be effective than a route with shorter passenger trips. The higher the percentage of longer trips the greater the potential for limited-stop service.

Demand Concentration

Limited-stop service will be most effective on a route with a high concentration of passengers at a few stops. To evaluate this concentration, boarding and alighting counts from either manual or electronically collected data are needed. The boarding and alighting counts for each stop should be added together to obtain the total demand at each stop and then stops should be sorted by (increasing) total demand and plotted as a cumulative demand distribution. A steeper curve implies higher concentration while a flatter curve implies a more dispersed distribution; higher concentration implies more effective service.

Figure 5-2 and Figure 5-3 present the cumulative demand curves for routes 49/X49 and route 20 respectively.

Figure 5-2 Cumulative Demand by Stop: Route 49/X49

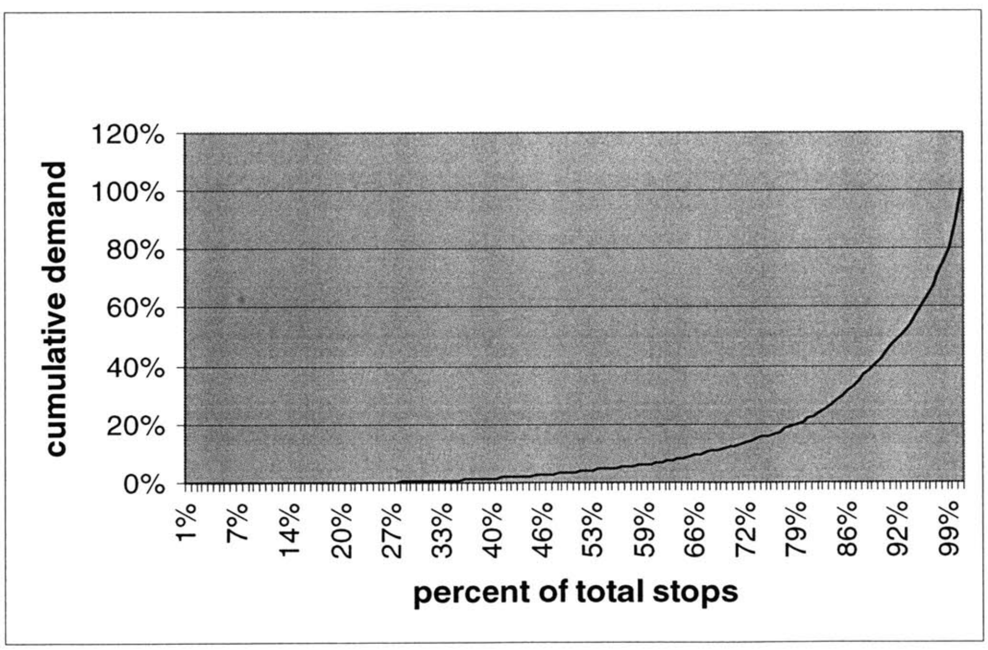
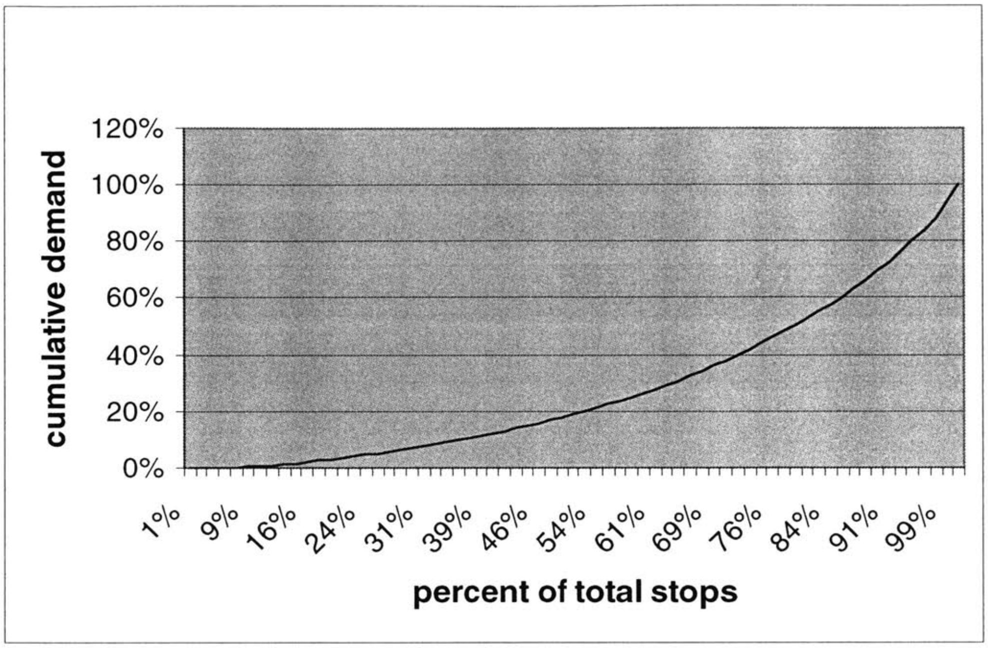


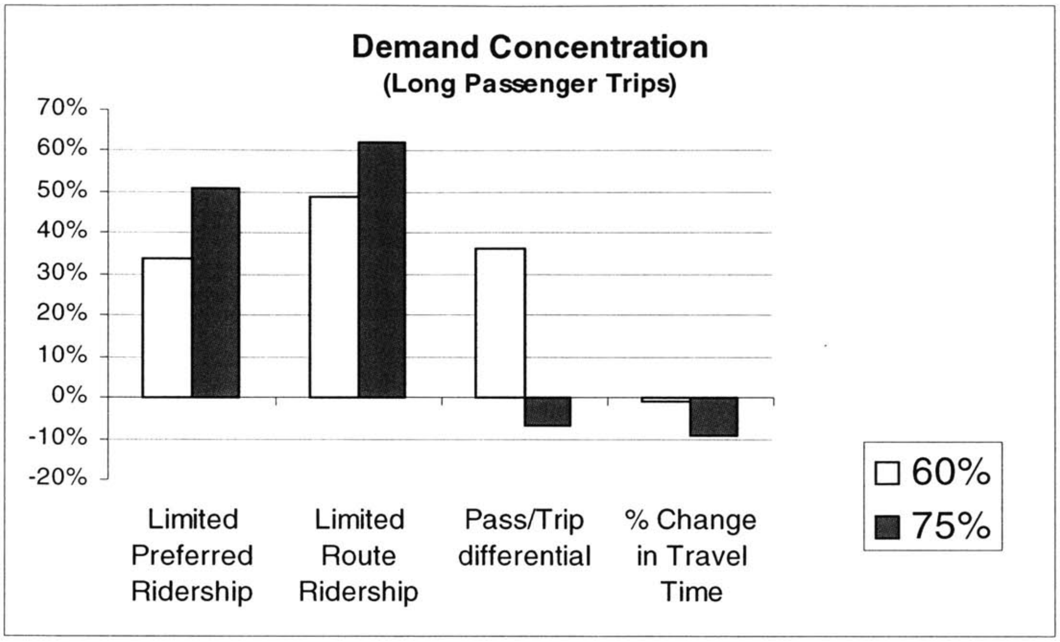
Figure 5-3 Cumulative Demand by Stop: Route 20



The x-axis is the cumulative percent of stops and the y-axis the cumulative demand. Figure 5-2 shows that for Route 49/X49 most of the demand is at a small percentage of the stops which can be seen from the shape of the curve which contains a steep rise beginning at about 75% of total stops which clearly contributes to the effectiveness of Route 49/X49. Figure 5-2 shows that for Route 20 the demand is more dispersed as indicated by its more linear structure which clearly contributes to its low potential for limited-stop service.

To reinforce this point, Figure 5-4 presents some of the results of the analysis on demand concentration and shows the effects of the demand concentration on the effectiveness of limited-stop service. The performance is clearly better when the demand concentration is higher.

Figure 5-4 Effect of Demand Concentration on Performance



** Pass/Trip differential: percent difference in limited over local, negative values imply higher limited productivity than local*

*** % change in Travel Time (un-weighted): negative (positive) values imply travel time savings (increases)*

Running Time Savings Potential

Clearly limited-stop service should be able to achieve running time savings if it is to be implemented on a corridor. To obtain travel time savings it is necessary that the limited-stop buses be able to pass local service buses. The street characteristics must be such that this is possible and this generally requires a wide roadway (at least two traffic lanes in each direction) although it might also be possible on a narrow roadway if the local bus operators consistently pull into the bus stop to pass. A wide roadway will also allow for higher travel time savings than a narrow roadway because the limited-stop bus will be able to operate in the more freely flowing lane, avoiding slowdowns from turning vehicles since the limited-stop service operates for a longer distance between stops than the local. Therefore, it is recommended that limited-stop service only be introduced on corridors with wide roadways.

5.2 Limited-Stop Design Guidelines

This section will propose guidelines for designing effective limited stop service once a promising corridor has been identified. These guidelines which cover stop spacing, running time, and limited-stop frequency share are based on the model applications presented in Chapter 4 of this thesis.

Stop Spacing

A well designed limited-stop service will have stops at all high demand stops, including all transfer points, but skip some or most of the moderate demand stops and all of the low demand stops. The stop spacing that should be selected is the widest stop spacing that will be effective since this will result in the highest travel time savings. Passenger trip lengths and the origin and destination demand concentration are connected to stop spacing and need to be taken into account in order to determine stop spacing.

Figure 5-2 (presented earlier) shows the cumulative demand curve for Route 49/X49. The demand curve in this case shows a steep rise around 70-75% of stops and the stop spacing on the X49 has a 72% reduction in the number of stops versus the local Route 49 service. The curve indicates that this stop spacing is appropriate since most of the demand is concentrated at less than 30% of the stops on the route. The range for the stop reduction on the limited-stop service versus the existing local service should be determined based on where the steep rise occurs in the curve, and the specific stops will be the transfer points and the stops that are included in the part of the graph after the rise.

Since longer passenger trips will result in greater potential travel time savings that could counteract increased access time, if passenger trips are long it would make sense to have slightly higher stop spacing and thus the range indicated by the cumulative demand curve can be refined based on this information. Limited-stop spacing can range from 0.3 miles up to 1 mile depending on the route characteristics.

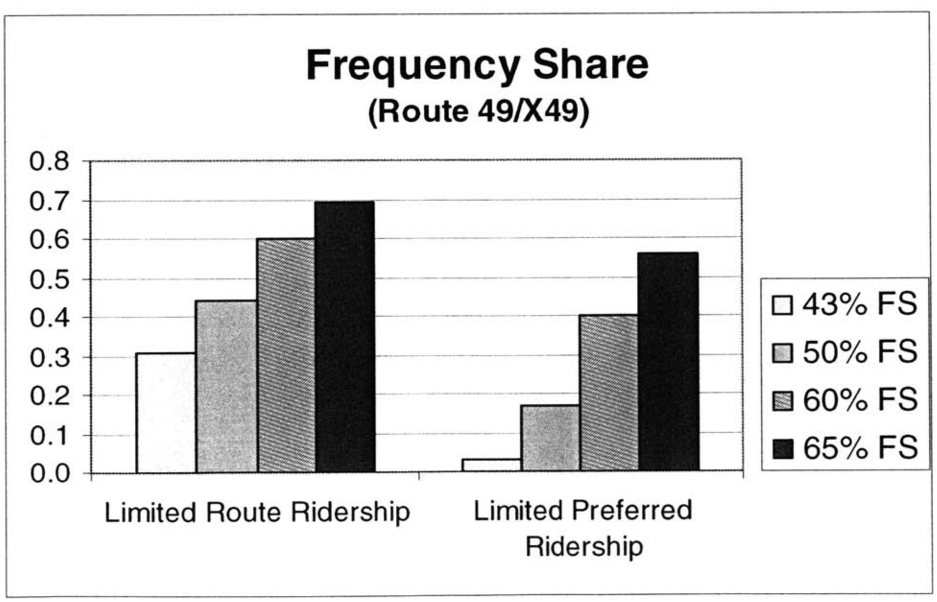
Running Time

Stop reduction and running time savings are linked and travel time savings are related to the interaction between the stop reduction and the nature of the traffic on the street. In general, route level travel time savings on a standard limited-stop service are between 15 and 25%. A minimum route level running time savings of 15% should be attainable on the route under the designated limited service stops. If this is not possible, it is not recommended that limited-stop service be implemented since it will not save enough in-vehicle time to attract limited preferred riders or encourage passengers to redistribute to limited service stops from nearby local stops. The agency must estimate what the travel time savings potential is on the route; AVL data, if available, can help with this process and Vissim or other micro-simulation software may also be useful.

Limited-Stop Frequency Share

One of the major finding of this thesis is that there should be a greater proportion of limited-stop service than local service. Figure 5-5 show the effect of increased frequency share for routes 49/X49 on limited-stop route ridership and limited preferred riders; both increase with the frequency share which is key to a successful limited-stop service.

Figure 5-5 Effect of Limited-Stop Frequency Share on Limited-Stop Ridership



**FS: Limited-Stop Frequency Share*

Once the stop spacing has been determined based on the design guidelines, the frequency share that should be selected should be at least 60% limited-stop service. A higher share of limited-stop service results in a greater redistribution to limited stops, which results in a greater percentage of passengers at limited service stops, which results in higher travel time savings and more effective service. A higher share of limited-stop service is also most likely to attract new riders who consider the local service too slow, but may ride the limited service if the expected wait time for the limited service is lower.

Increasing the frequency split to greater than 60% has a significant impact on the headways, especially when the existing headway is greater than five minutes, since the local headway will increase beyond 10 minutes. Once the local headway is greater than 12 minutes it is better to set it to a reliable 15 (or even 20) minute clock-face headway instead. This is effectively a method for increasing stop spacing or reducing the number of stops on a route, since this will create a local service with clock face headways for passengers with limited mobility, but effectively increase stop spacing and thus reduce travel time for the remaining passengers. Since it is often politically difficult to increase stop spacing, this provides an approach to doing so without removing the local service entirely.

6 CONCLUSION

This chapter summarizes the results of this research. It will briefly describe the model that was created to analyze limited-stop service and to develop the guidelines and it will review the results of the analysis. Also included in this chapter are recommendations to CTA regarding their overall strategy with respect to limited-stop service as well as the specific routes analyzed in this thesis. Finally, suggestions are made for future work on this subject.

6.1 Summary

Many transit agencies run both limited-stop and local service along some of their heavy ridership corridors. The primary benefit of limited-stop bus service is higher speed which results in reduced running time and thus reduced travel time for passengers. This reduced travel time can improve the service quality for existing passengers and can increase ridership on the route, thus both passengers and the agency can benefit from limited-stop service. However, this strategy also results in increased access time, and in increased wait time for some passengers, especially when the strategy is considered in a resource neutral context, meaning that no additional resources are added and the creation of the limited-stop bus service requires splitting the existing all-local resources between the new limited-stop service and the local service. This thesis focuses primarily on resource neutral limited-stop service. Creating an effective limited-stop bus service requires careful planning and this is the primary motivation for the analytically based guidelines developed in this thesis. There were three primary objectives in this thesis. The first was to create a model that could be used to analyze limited-stop bus service. The second was to apply the model to CTA case studies. The third was to develop guidelines that transit agencies can use for the evaluation and design of both new and existing limited-stop bus service.

The first part of this research involved a review of the existing literature related to limited-stop bus service including both academic sources and the experience of transit agencies. Often the most detailed information was available from the transit agencies, including Chicago Transit Authority, New York City Transit, and Los Angeles County

MTA; there is little academic research directly on this topic. This research is different from previous research in that the focus is entirely on limited-stop bus service and an analytic method was used to evaluate limited stop service with the goal of developing general design guidelines for such services.

The model created is a tool which is used to evaluate a specific service configuration defined by both the local and limited-stop headways and stops. The model calculates travel times, and assigns existing demand to limited and local stops and to limited and local routes, based on minimum passenger (weighted) travel time. This assignment is applied at both the origin and destination. The model then calculates several measures of effectiveness which are used to compare different configurations; these measures include market share (local preferred, limited preferred, and choice passengers), stop and route assignment (number of passengers selecting the limited service stops and limited-stop service), net change in passenger travel time (weighted and un-weighted), and finally productivity (passengers per trip and per vehicle hour for the local and limited-stop service).

The model was used to analyze two CTA cases: Western Avenue local Route 49 and limited-stop Route X49, and the Madison Avenue Route 20. Western Avenue was used to validate the model and its underlying assumptions; both Western Avenue and Madison Avenue were used as application case studies using the model. The analysis of Western Avenue and Madison Avenue involved testing alternative frequency configurations; alternate stop spacing configurations were analyzed only for Madison Avenue. Specific recommendations from these case studies will be presented in the next section of this chapter.

The results of the analysis can be organized as two sets of general guidelines: corridor (or route) potential for limited stop service and limited-stop service design. The results of the analysis show that the concentration of origins and destinations defined as the percentage of passenger trips that begin and end at or near a limited stop appears to be as critical to the effectiveness of the route as passenger trip length. Both long passenger trips and concentrated demand are needed for highly effective limited-stop service. Additional factors that affect the viability of the route are the total ridership, the available resources, and the route level running time savings achievable.

Once it has been established that limited-stop service is viable on a route, the next step is to determine the specific stop spacing and frequency share that will be most effective. The stop spacing on the limited-stop service is determined by placing stops at the highest demand points with the goal of attaining the widest effective stop spacing so that the maximum route level travel time savings can be achieved. One of the major findings of this thesis concerns the frequency share on the limited-stop service; the analysis shows that limited-stop service is generally most effective at 50%, or more, of the total service. The next section will briefly review the results of the specific case studies and provide both general recommendations to CTA and specific recommendations regarding these routes.

6.2 CTA Recommendations

The CTA case studies considered in this thesis are Western Avenue routes 49 and X49, and Madison Avenue Route 20.

Western Avenue Route 49 and X49 Recommendations

The analysis of routes 49 and X49 focused entirely on frequency since the X49 is an existing limited-stop service and the all-local O-D demand matrix is not known so the model cannot be used to evaluate stop spacing changes under these circumstances. However, the existing stop spacing was found to be quite effective so there does not appear to be any reason to change it.

The current limited frequency share of 43% appears to be too low to generate significant net benefits: the measures of effectiveness improve as the frequency share is increased to 60%. It is recommended that CTA increase the frequency share on the limited route to at least 60% of total service rather than the existing 43% limited frequency share. The recommended peak headway on the limited-stop service, if the frequency share is increased to 60% should be 7 minutes (11 minute local headway), or alternatively if frequency share is increased to about 70% then the limited-stop headway should be 6 minutes (15 minute local headway)

Madison Avenue Route 20 Recommendations

The analysis on route 20 included alternative stop spacing and frequencies. Two stop spacing configurations were considered: the first, C1, has an average stop spacing of 0.37 miles, a 63% reduction in the number of stops over the local service, and a 20% route level running time reduction, and the second, C2, has an average stop spacing of 0.30 miles, a 57% reduction in the number of stops over the local service, and a 15% route level running time reduction.

As a consequence of the demand pattern on the route, comprised of relatively short passenger trip lengths (60% of trips less than 2 miles) and evenly distributed demand along the route (see Figure 5-3), neither C1 nor C2 was found to be effective. The short passenger trip lengths are likely a consequence of the presence of the parallel Green Line service half a mile north of Madison Avenue. Passengers seeking to save travel time can walk to the Green Line; passengers who take longer trips are more likely to do this, and thus most trips on Route 20 are relatively short trips. The presence of the Green Line makes limited-stop service on Madison Avenue unnecessary and the analysis further supports this claim.

C2 was found to be more effective than C1: the C2 configuration shows viable productivity measures when the frequency share is increased to 65%; however, all of the possible frequency configurations result in travel time increases over the existing all local service. While it is true that limited route riders and some choice passengers do save time, the overall increase in passenger travel time is still significant, resulting in a net weighted passenger travel time increase of 10% for C2 at 65% frequency share (Table

4-12). Thus limited-stop service will not be effective on Madison Avenue and is not recommended.

A significant difference between route 20 and all existing CTA limited-stop services is that Route 20 serves the downtown area which would require that a limited-stop service on this corridor make many more stops in the downtown area than limited stop service typically does and that it will be subject to significant traffic congestion and traffic signal delay, reducing potential travel time savings. To address this problem, CTA is considering running the limited-stop service on a separate street from the local service. This configuration effectively forces each passenger to make a route choice decision when they make the stop choice decision.

The market share measures when both services are run on the same route predict that under stop spacing C2 and 65% frequency share, the percentage of limited preferred passengers is 47%. These are the passengers who will take only the limited-stop service and will likely take it even if it runs on a separate street. 23% of passengers are choice riders and whether they opt for the limited-stop service or the local service these passengers will be subject to higher wait time than they would if service remained all local or if limited-stop service operated on the same street as the local service. As a result both net weighted and un-weighted passenger travel times will increase further if the limited-stop service is run on a separate street, and the service will be even less effective than these numbers indicate. This strategy would have negative consequences for existing route 20 passengers and is not recommended.

General Recommendation to CTA

The guidelines presented in this thesis will be useful in evaluating the corridor potential for limited-stop service and for the design of limited-stop service. Currently, the frequency share for all CTA limited-stop routes is less than or equal to 50%, and thus applying the frequency share guideline would be a change to CTA practice.

In general, it is not recommended that limited-stop service be introduced on routes that parallel a rail line (unless the rail line is near capacity) since a high frequency and high speed alternative already exists. It is also not recommended that limited-stop service be introduced on routes that serve the downtown area since there are too many high volume stops and reduced potential for travel time savings. Longer routes such as the 49/X49 on Madison Avenue and possibly Route 9 on Ashland which do not parallel rail lines or serve the downtown area have the greatest potential for effective limited-stop service. Existing limited-stop routes 55/X55 on Garfield and the 80/X80 Irving Park are long enough to have long passenger trips and do not parallel rail lines or serve the downtown area and thus it appears that limited-stop service can be effective on these routes. Limited-stop service as a strategy at CTA does not appear to be greatly expandable considering route length, headway, proximity to a rail line, and whether the route goes though the downtown area.

Currently at CTA, service is marketed such that the local service is the primary service (i.e. 49) and the limited-stop service is the secondary service (i.e. X49). Since the frequency share is recommended to be at least 50% on these routes, the limited-stop service is the more frequent service and should be the primary service. For marketing purposes, it may be better to change this perspective in both the agency and for passengers by designating the limited-stop route as the primary route while the local route is the secondary route.

6.3 Future Work

This thesis covers basic limited stop service, assuming that no additional BRT components are present such as signal priority or dedicated lanes. The effects of changing the limited-stop frequency share and stop spacing are explored in detail. Passenger trip length and the origin to destination demand pattern are analyzed to determine the effect of each of these route attributes on the effectiveness of limited stop service. However, there are additional aspects of limited-stop bus service that are briefly discussed in this thesis but are not considered in detail.

Extensions of the Model

The model is an assignment model and does not predict increases in demand. Updating the model with a demand forecasting capability would be an important extension. This capability was not necessary for the purpose of this thesis but it would be valuable to be able to predict increased ridership as a result of limited-stop service. Revising the model to make it easier to use would be another significant enhancement. The inputs to the model require some processing before these can be input to the model: AVL and APC data must be processed to remove outliers, to determine the average stop to stop running times, and produce the total boardings and alightings per stop. In addition, the O-D demand matrix is currently created externally from the counts and input to the model. Thus a model based on the one in this thesis that could do some of this processing in addition to its existing capabilities would save the user time and make it more feasible for the model to be used by transit agencies. Finally, the model evaluates a specific configuration of limited-stop service; however, if the model were redesigned so that it could iterate to test several configurations, this would enhance the model capabilities

Span of Service

An important service decision issue that must be addressed when instituting limited-stop service is span of service. This issue is mentioned in the literature but is not covered in detail. Some agencies run limited-stop service on certain routes only during the peak periods, and sometimes only in the peak direction during the peak periods, while other routes run at all hours during the week and sometimes also on weekends. Span of service guidelines on limited-stop service is one area that needs further research and is both a service design issue and a marketing issue.

Branding

Branding is another topic that is not covered in detail in this thesis. One of the issues that CTA has found with their limited-stop routes is that since there is no branding on CTA limited-stop buses, passengers cannot determine in advance if a limited-stop bus is approaching and thus they are more likely to board the first bus that arrives. The effects of branding and how branding might enhance limited-stop service is another area that needs further research.

Limited-Stop service in the context of Bus Rapid Transit (BRT)

Limited-stop service is one possible strategy for improving bus service. BRT is another strategy which encompasses many elements, one of which is longer stop spacing. This research focuses on limited-stop service, operating on the same street as a local service, and without any additional BRT attributes. BRT service does not generally operate on the same street as local service, and this is a significant departure from the focus of this thesis. Further research would be needed on the effects of increased stop spacing in this situation.

The MTA's Metro Rapid service is partway between limited-stop service and BRT and does operate on the same street as a local service. Metro Rapid has signal priority on the Rapid buses but not on the local buses, thus the differential between the running times on the two services is higher than on standard limited-stop service. Since limited-stop service is a strategy to improve overall bus service, local buses should also be given signal priority so that all buses operate at faster speed (more efficiently). If this were the case then signal priority would not necessarily result in a higher differential between the two services. Off-vehicle fare collection is often a component of BRT, but since it shortens dwell times, it may potentially reduce the running time differential between the limited-stop and the local service. Thus, BRT components may not necessarily increase the differential in the level of service between the limited-stop and the local service, and may actually decrease it. This is an area that needs further research.

Service reliability in the context of limited-stop service

Some agencies have found that limited-stop service helps to improve service reliability on routes and reduce bus bunching. This is not directly explored in this thesis, but it has been assumed in the analysis that limited-stop service is somewhat more reliable than the local service since it stops at fewer stops. This is an area that can be explored in more detail in future research.

Understanding Passenger Behavior

The assignment process in this research used an all or nothing market share assignment. This produced reasonable results and thus a more complex model was not necessary for this thesis, but it would still be valuable to try to gain a more in depth understanding of passenger behavior. Initially analysis was done on survey data from previously conducted CTA market research surveys, but the data available was not applicable to understanding passenger behavior with respect to the assignment process. A typical market research survey is not likely to provide the data necessary to develop a good understanding of this issue or to develop a more complex model or assignment process. A specially designed survey instrument may be needed for this purpose.

Real time information is a specific area of passenger behavior. If passengers know how long the wait is until the next limited-stop bus then they are more likely to wait for it, assuming that the wait time is reasonably short. Real time information would likely result in choice passengers having a much greater likelihood of taking the limited-stop service rather than the local. The effects of real time information on the effectiveness of limited-stop service, is another area of future research.

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49/X49 NB O-D Matrix (Limited service stops presented only)

Demand	79TH TERMINAL	71ST STREET	MARQUETTE	63RD STREET	59TH STREET	GARFIELD (n.leg)/55TH ST.	51ST STREET	ORANGE LINE STATION	47TH STREET	43RD STREET	ARCHER	35TH STREET	26TH STREET	CERMAK	BLUE LINE (DOUGLAS)	16TH STREET	ROOSEVELT	HARRISON	VAN BUREN	JACKSON	MADISON	GRAND	CHICAGO	DIVISION	NORTH AVENUE	MILWAUKEE	ARMITAGE	FULLERTON	ELSTON/DIVERSEY	BELMONT/CLYBOURN	ADDISON	IRVING PARK	MONTROSE	LELAND	LAWRENCE	FOSTER	BERWYN
79TH TERMINAL		13	9	49	0	10	2	40	6	0	1	1	2	1	0	0	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
71ST STREET			5	37	0	10	2	44	7	0	1	1	3	2	0	0	2	0	2	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
MARQUETTE				20	0	8	2	39	6	0	1	1	3	2	0	0	2	0	2	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
63RD STREET					0	14	3	75	12	0	2	1	7	4	0	1	4	0	4	0	1	0	1	2	1	2	0	0	0	1	1	0	0	0	0	0	0
59TH STREET						0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GARFIELD (n.leg)/55TH ST.							1	41	8	0	2	1	6	4	0	1	4	0	4	0	1	0	1	2	1	2	0	0	0	1	1	0	0	0	0	0	0
51ST STREET								4	1	0	0	0	1	1	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
ORANGE LINE STATION									3	0	2	1	8	5	0	1	6	1	6	0	2	0	1	4	1	3	1	0	1	1	2	0	0	0	0	0	0
47TH STREET										0	1	1	6	4	0	1	4	0	4	0	1	0	1	3	1	2	0	0	0	1	1	0	0	0	0	0	0
43RD STREET											0	0	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARCHER												0	3	2	0	0	3	0	3	0	1	0	1	2	1	2	0	0	0	1	1	0	0	0	0	0	0
35TH STREET													1	1	0	0	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
26TH STREET														1	0	0	2	0	3	0	1	0	1	2	1	2	0	0	0	1	1	0	0	0	0	0	0
CERMAK															0	0	5	1	7	0	2	0	2	6	2	5	1	0	1	2	4	1	0	1	0	0	0
BLUE LINE (DOUGLAS)																0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
16TH STREET																	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROOSEVELT																		0	2	0	1	0	1	3	1	3	1	0	1	1	2	0	0	0	0	0	0
HARRISON																			0	0	0	0	0	2	1	2	0	0	0	1	2	0	0	0	0	0	0
VAN BUREN																				0	0	0	1	4	1	4	1	0	1	2	3	1	0	0	0	0	0
JACKSON																					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MADISON																						0	0	2	1	2	0	0	1	1	2	0	0	0	0	0	0
GRAND																							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHICAGO																								3	2	6	1	0	2	4	7	2	0	1	0	0	0
DIVISION																									1	4	1	0	1	3	6	1	0	1	0	0	0
NORTH AVENUE																										3	1	0	2	5	9	2	0	2	0	0	0
MILWAUKEE																											0	0	2	5	11	3	0	2	0	0	0
ARMITAGE																												0	1	2	4	1	0	1	0	0	0
FULLERTON																													0	0	0	0	0	0	0	0	0
ELSTON/DIVERSEY																														4	12	4	0	3	0	0	0
BELMONT/CLYBOURN																															10	4	0	4	0	0	0
ADDISON																																8	0	12	0	1	1
IRVING PARK																																	1	26	0	3	3
MONTROSE																																		1	0	0	0
LELAND																																			0	7	9
LAWRENCE																																				0	1
FOSTER																																					0
BERWYN																																					

49/X49 Southbound O-D (Limited service stops presented only)

Demand	BERWYN	FOSTER	LAWRENCE	LELAND	MONTROSE	IRVING PARK	ADDISON	BELMONT	ELSTON/DIVERSEY	FULLERTON	ARMITAGE	CORTLAND	NORTH AVENUE	DIVISION	CHICAGO	GRAND	JACKSON	BLUE LINE (CONGRESS)	HARRISON	ROOSEVELT	16TH STREET	21ST STREET	CERMAK	26TH STREET	35TH STREET	ARCHER	43RD STREET	47TH STREET	ORANGE LINE STATION	51ST STREET	55TH STREET/GARFIELD	59TH STREET	63RD STREET	MARQUETTE	71ST STREET	79TH TERMINAL
BERWYN		6	3	32	8	9	40	6	0	6	1	18	0	13	4	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FOSTER			2	17	5	5	24	3	0	4	1	11	0	9	2	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LAWRENCE				5	3	5	26	4	0	5	1	14	0	11	3	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LELAND					1	2	13	2	0	3	1	7	0	6	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MONTROSE						3	19	3	0	4	1	13	0	10	3	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IRVING PARK							14	3	0	5	1	16	0	13	4	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ADDISON								1	0	2	1	8	0	7	2	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BELMONT									0	3	1	13	0	13	4	1	1	1	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
ELSTON/DIVERSEY										0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FULLERTON											1	20	0	30	10	4	3	4	0	4	0	0	2	1	0	1	0	1	2	0	0	0	0	0	0	0
ARMITAGE												1	0	4	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CORTLAND													0	57	22	9	8	11	0	11	0	1	5	4	1	3	0	2	6	0	1	0	0	0	0	1
NORTH AVENUE														0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DIVISION															5	3	4	5	0	5	0	0	3	2	0	2	0	1	3	0	1	0	0	0	0	1
CHICAGO																3	6	8	0	10	0	1	5	4	1	4	0	3	7	1	1	0	0	0	0	2
GRAND																	2	3	0	3	0	0	2	2	0	1	0	1	3	0	0	0	0	0	0	1
JACKSON																		0	0	1	0	0	1	1	0	1	0	1	2	0	0	0	0	0	0	0
BLUE LINE (CONGRESS)																			0	3	0	0	3	3	0	3	0	2	6	1	1	0	0	0	0	2
HARRISON																				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROOSEVELT																					0	0	3	3	1	4	0	3	8	1	2	0	0	0	0	2
16TH STREET																						0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
21ST STREET																							0	1	0	2	0	1	4	0	1	0	0	0	0	1
CERMAK																								2	1	5	0	5	14	1	3	0	0	0	0	4
26TH STREET																									0	3	0	3	8	1	2	0	0	0	0	3
35TH STREET																										0	0	0	1	0	0	0	0	0	0	0
ARCHER																											0	3	9	1	2	0	0	0	0	5
43RD STREET																												1	4	0	1	0	0	0	0	4
47TH STREET																													5	1	4	0	0	0	1	15
ORANGE LINE STATION																														1	7	1	1	0	2	30
51ST STREET																															1	0	0	0	1	9
55TH STREET/GARFIELD																																0	1	0	2	27
59TH STREET																																	0	0	0	0
63RD STREET																																		0	0	1
MARQUETTE																																			0	0
71ST STREET																																				17
79TH TERMINAL																																				

Route 20 (eastbound) O-D Matrix (page 1)

	AUSTIN	MASON	MAYFIELD	MENARD	WALLER	PARKSIDE	CENTRAL	PINE	LOTUS	LONG	LOCKWOOD	LARAMIE	LECLAIRE	LAVERGNE	LAMON	CICERO	KILPATRICK	KENTON	KILBOURN	KOSTNER	KILDARE	KEELER	KARLOV	MADISON + PULASKI	SPRINGFIELD	HAMLIN	CENTRAL PARK	ST LOUIS	HOMAN	SPAULDING	KEDZIE	ALBANY	SACRAMENTO
AUSTIN		0	0	0	0	1	6	0	2	1	1	5	2	2	0	4	2	2	1	2	5	1	1	6	1	1	1	0	5	0	9	0	0
MASON			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAYFIELD				0	0	0	1	0	1	0	0	1	0	1	0	1	0	0	0	1	1	0	0	2	0	0	0	0	1	0	3	0	0
MENARD					0	0	2	0	1	0	0	2	1	1	0	1	1	1	0	1	2	1	0	2	0	1	0	0	2	0	4	0	0
WALLER						0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	1	0	0
PARKSIDE							0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0	0	1	0	0	0	0	1	0	2	0	0
CENTRAL								0	1	0	0	4	1	2	0	4	2	2	1	3	7	2	1	8	1	2	1	0	7	1	13	0	1
PINE									0	0	0	1	0	0	0	1	0	0	0	1	1	0	0	1	0	0	0	0	1	0	2	0	0
LOTUS										0	0	1	0	1	0	1	1	1	0	1	2	1	0	3	0	1	1	0	3	0	5	0	0
LONG											0	1	0	0	0	1	0	0	0	1	1	0	0	2	0	0	0	0	2	0	3	0	0
LOCKWOOD												1	0	1	0	1	1	1	0	1	3	1	0	4	0	1	1	0	3	0	6	0	0
LARAMIE													0	1	0	2	1	1	1	2	5	1	1	6	1	1	1	0	6	0	12	0	0
LECLAIRE														0	0	1	0	0	0	1	2	1	0	3	0	1	1	0	3	0	5	0	0
LAVERGNE															0	1	0	1	0	1	3	1	0	4	0	1	1	0	4	0	9	0	0
LAMON																0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	2	0	0
CICERO																	0	1	0	2	4	1	1	7	1	2	1	0	7	1	15	0	1
KILPATRICK																		0	0	0	1	0	0	1	0	0	0	0	1	0	3	0	0
KENTON																			0	0	0	0	0	1	0	0	0	0	1	0	1	0	0
KILBOURN																				0	1	0	0	2	0	0	0	0	2	0	5	0	0
KOSTNER																					1	0	0	2	0	1	1	0	3	0	7	0	0
KILDARE																						0	0	2	0	1	1	0	3	0	7	0	0
KEELER																							0	1	0	0	0	0	2	0	4	0	0
KARLOV																								1	0	0	0	0	2	0	6	0	0
MADISON + PULASKI																									0	1	1	0	5	0	12	0	1
SPRINGFIELD																										0	0	0	1	0	3	0	0
HAMLIN																											0	0	3	0	7	0	0
CENTRAL PARK																												0	0	0	1	0	0
ST LOUIS																													0	0	0	0	0
HOMAN																														0	4	0	0
SPAULDING																															0	0	0
KEDZIE																																0	0
ALBANY																																	0
SACRAMENTO																																	

Route 20 O-D Matrix (page 2)

	FRANCISCO	CALIFORNIA	WASHTENAW	ROCKWELL	CAMPBELL	WESTERN	OAKLEY	LEAVITT	HOYNE	DAMEN	UNITED CENTER	WOOD	PAULINA	ASHLAND	LAFLIN	LOOMIS	THROOP	RACINE	ABERDEEN	MORGAN	PEORIA	JEFFERSON	CANAL	FRANKLN	LASALLE	DEARBORN BLUE LINE	WASHINGTON + STATE	WABASH	MICHIGAN + RANDOLPI	SOUTH WATER	EAST WACKER	WACKER + STETSON	COLUMBUS	COLUMBUS + S WATEF
AUSTIN	1	1	0	0	1	2	1	0	2	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
MASON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAYFIELD	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MENARD	0	1	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WALLER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PARKSIDE	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CENTRAL	1	2	0	0	1	3	2	0	2	1	0	0	1	2	1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0
PINE	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTUS	0	1	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
LONG	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOCKWOOD	1	1	0	0	1	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0
LARAMIE	1	2	0	0	1	3	2	0	2	1	0	0	1	2	1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0
LECLAIRE	1	1	0	0	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
LAVERGNE	1	1	0	0	1	2	2	0	2	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
LAMON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CICERO	1	2	0	0	1	4	3	1	3	2	0	1	1	2	1	0	0	0	0	1	0	1	1	2	2	1	1	1	1	0	0	0	0	0
KILPATRICK	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KENTON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KILBOURN	1	1	0	0	0	1	1	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0
KOSTNER	1	1	0	0	1	2	1	0	2	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
KILDARE	1	1	0	0	1	2	2	0	2	1	0	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0
KEELER	0	1	0	0	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0
KARLOV	1	1	0	0	1	2	1	0	2	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
MADISON + I	1	3	0	0	1	4	3	1	4	2	0	1	2	3	1	0	0	0	0	1	0	1	2	2	3	2	2	2	1	0	0	0	0	0
SPRINGFIEL	0	1	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0
HAMLIN	1	2	0	0	1	3	2	0	3	1	0	0	1	2	1	0	0	0	0	1	0	1	1	2	2	1	1	1	1	0	0	0	0	0
CENTRAL PA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ST LOUIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HOMAN	1	2	0	0	1	3	3	1	3	2	0	1	2	3	1	0	0	0	0	1	0	1	2	2	3	2	2	2	1	0	0	0	0	0
SPAULDING	0	0	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0
KEDZIE	1	2	0	0	1	3	3	1	4	2	0	1	2	3	1	0	0	0	0	1	0	2	3	3	4	2	3	2	1	0	0	0	0	0
ALBANY	0	0	0	0	0	1	1	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
SACRAMENT	0	0	0	0	0	1	1	0	1	1	0	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0

Route 20 O-D Matrix (page 3)

	FRANCISCO	CALIFORNIA	WASHTENAW	ROCKWELL	CAMPBELL	WESTERN	OAKLEY	LEAVITT	HOYNE	DAMEN	UNITED CENTER	WOOD	PAULINA	ASHLAND	LAFLIN	LOOMIS	THROOP	RACINE	ABERDEEN	MORGAN	PEORIA	JEFFERSON	CANAL	FRANKLN	LASALLE	DEARBORN BLUE LINE	WASHINGTON + STATE	WABASH	MICHIGAN + RANDOLPH	SOUTH WATER	EAST WACKER	WACKER + STETSON	COLUMBUS	COLUMBUS + S WATER
FRANCISCO		0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
CALIFORNIA			0	0	0	2	2	0	3	1	0	1	1	3	1	0	0	0	0	1	0	1	3	3	3	2	2	2	1	0	0	0	0	0
WASHTENAW				0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
ROCKWELL					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CAMPBELL						0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
WESTERN							1	0	2	1	0	1	1	3	1	0	0	0	0	1	0	2	3	4	5	3	4	3	1	1	1	0	0	0
OAKLEY								0	1	1	0	0	1	2	1	0	0	0	0	1	0	1	2	2	3	2	2	2	1	0	0	0	0	0
LEAVITT									0	0	0	0	1	2	1	0	0	0	0	1	0	1	2	2	3	2	2	2	1	0	0	0	0	0
HOYNE										0	0	0	0	1	0	0	0	0	0	1	0	1	1	2	2	1	2	1	1	0	0	0	0	0
DAMEN											0	0	0	1	0	0	0	0	0	1	0	1	2	2	3	2	2	2	1	0	0	0	0	0
UNITED CENTER												0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WOOD													0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
PAULINA														0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0
ASHLAND															0	0	0	0	0	1	0	2	4	4	6	4	4	4	2	1	1	0	0	0
LAFLIN																0	0	0	1	2	0	3	6	8	10	6	8	7	3	2	1	1	0	0
LOOMIS																	0	0	0	1	0	1	3	4	5	3	4	3	1	1	1	0	0	0
THROOP																		0	0	1	0	4	7	9	12	8	9	8	4	2	2	1	0	0
RACINE																			0	1	0	2	5	6	8	5	6	6	3	1	1	1	0	0
ABERDEEN																				0	0	2	3	4	6	4	5	4	2	1	1	0	0	0
MORGAN																					0	2	4	6	8	5	6	6	3	1	1	1	0	0
PEORIA																						0	0	0	0	0	0	0	0	0	0	0	0	0
JEFFERSON																							1	1	2	2	2	2	1	1	1	0	0	0
CANAL																								13	26	22	28	29	14	7	7	3	0	1
FRANKLN																									1	1	1	2	1	0	0	0	0	0
LASALLE																										1	2	2	1	1	1	0	0	0
DEARBORN BLUE LINE																											2	5	3	2	2	1	0	0
WASHINGTON + STATE																												5	4	3	3	2	0	1
WABASH																													4	4	5	2	0	1
MICHIGAN + RANDOLPH																														3	5	2	0	1
SOUTH WATER																															3	2	0	1
EAST WACKER																																1	0	1
WACKER + STETSON																																	0	1
COLUMBUS																																		0
COLUMBUS + S WATER																																		